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TECHNICAL SUPPORT FOR TACTICAL SHELTERS

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A program was conducted to provide a wide range of technical support activity for tactical shelters. Work was carried out in eight general technical areas: (a) materials testing and evaluation, (b) armor development, (c) electromagnetic shielding and detection, (d) long-term outdoor exposure, (e) testing techniques, (f) repair, (g) redeployment, and (h) general support.

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PREFACE

This report describes work performed under Air Force Contract F33615-85-C-5094 during the period August 1985 to January 1991. The program was administered under the direction of the Systems Support Division of the Materials Laboratory, Wright Research and Development Center, Wright-Patterson Air Force Base, Ohio. Mr. Frank Fechek (WL/MLSE) was the Program Project Engineer.

The University of Dayton Research Institute (UDRI) was the prime contractor with Mr. D. Robert Askins serving as Principal Investigator. The Mission Research Corporation (MRC) was under subcontract to UDRI for a portion of the work with Messrs. Paul Trybus and David Schafer directing their effort. Mr. Ronald Kuhbander of UDRI directed many of the project activities on this program and prepared a substantial portion of this final report.

Acknowledgements are extended to Dr. Stephan Bless, Mr. Roger Rondeau, Mr. David Kemp, Dr. Thomas Whitney, and Mr. Daniel Bowman of the UDRI for major contributions to the program and to many other UDRI personnel for carrying out the laboratory work.

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LIST OF ACRONYMS

VOC	volatile organic compound
EMI	electromagnetic interference
RFI	radio frequency interference
HAMS	hardness assurance monitoring system
RF	radio frequency
ASF	Army standard family
UDRI	University of Dayton Research Institute
FRP	floating roller peel or fiber reinforced plastic
CDP	climbing drum peel
ISO	International Organization for Standardization
ASTM	American Society for Testing and Materials
DOD	Department of Defense
OFPL	optimized Forest Products Laboratory
WRDC/MLSE	old symbol for Wright Research and Development Center/ Materials Laboratory, Materials Engineering Branch-- WRDC has recently been changed to WL, Wright Laboratory, Wright-Patterson Air Force Base
STRNC-UST	symbol for Tactical Shelter Branch of Aeromechanical Electronics Directorate, Natick R&D Center
ESD/AVMS	old symbol for Electronic Systems Division/Air Force Tactical Shelters Office--AVMS has recently been changed to AVDS, Hanscom AFB
AFTS	Air Force tactical shelters
FSP	fragment simulating projectile
AP	armor piercing
GRP	glass-reinforced plastic
SLAP	saboted light armor piercing
EM	electromagnetic
CERL	Construction Engineering Research Laboratory
MRC	Mission Research Corporation
ASM	model name of instrument manufactured by ASM Products, Inc.
SIMS	model name of instrument manufactured by Ray-Proof Shielding Systems Corp. that stands for "Shielding Integrity Monitoring System"

LIST OF ACRONYMS (Continued)

SELDS	model name of instrument manufactured by Eaton Corp. that stands for "Shielded Enclosure Leak Detection System"
USATTC	U.S. Army Tropic Test Center
TTC	Tropic Test Center
MCS	Maximum Cleavage Stress

1. INTRODUCTION

The Department of Defense (DOD) has used tactical mobile shelters for a wide variety of functions for many years. These shelters are located throughout the world and can encounter a wide variety of natural and man-made environments. A great deal of activity has been carried out during the last 15 years to increase the durability and survivability of tactical shelters.

The criteria by which shelter durability and survivability are defined involve a diverse cross-section of characteristics and technologies. These include the following considerations:

(a) structural integrity,
(b) environmental (climate) resistance,
(c) nuclear effects,
(d) electromagnetic effects,
(e) armor,
(f) repair and maintenance, and
(g) manufacturing.

The program described in this report involved a spectrum of activities in most of these areas including collection, development, and dissemination of information useful to the shelter community. Specifically, work was carried out in the areas of:

(a) materials testing and evaluation,
(b) armor development,
(c) electromagnetic shielding and detection,
(d) long-term outdoor exposure,
(e) testing techniques,
(f) repair,
(g) redeployment, and
(h) general support activities.

Detailed descriptions of these activities are presented in the following sections.

2. SUMMARY

A program was conducted to provide technical support for tactical shelters. Work was carried out in seven general technical areas.

In the area of materials testing and evaluation, structural film adhesives used in shelter manufacturing were thoroughly characterized to establish that they met the requirements of the applicable ASTM specification. Kraft paper honeycomb core was also tested to determine whether it met the requirements of the ASTM specification for core in shelter structures. Honeycomb sandwich panels and adhesively bonded specimens were tested to determine if the materials and processes used in their manufacture delivered property levels required in various ASTM shelter specifications. Water-based adhesive primers with low VOC (volatile organic compound) levels were evaluated to see if the properties of bonded joints prepared with these primers could deliver equivalent property levels to those achievable with state-of-the-art solvent-based corrosion-inhibiting primers. The motivation for this study was the imposition of lower VOC limits in some areas of the country in which shelters are manufactured or repaired. An investigation was carried out to try to determine possible causes of a debonding problem that occurred during the manufacture of roof panels for portable shelters. Post-test analyses were carried out on an experimental hardened shelter that sustained unexpected damage during a simulated nuclear test. Specimens taken from this shelter were tested to determine whether the minimum property levels required in the applicable materials specification were met. Water is used in the preparation of processing solutions and in the rinsing of aluminum prior to adhesive bonding during shelter manufacture. Experiments were conducted to determine the effect of various chloride levels in this water on resulting bond strength levels and bond durability. The maximum permissible chloride level is not the same in various ASTM surface preparation specifications and some regionally distributed potable sources do not meet some of the permissible chloride levels.

In the area of armor development, two comprehensive investigations were carried out to develop armor systems for tactical shelters capable of defeating armor piercing small arms fire and ballistic fragments.

In the area of electromagnetic shielding and detection, two investigations were carried out. One involved the development of an automated, integrated EMI/RFI shielding monitoring system capable of scanning the entire shelter surface over the frequency range 100 kHz - 500 MHz, and the development of a hand-held 12 GHz "sniffer." A prototype system was constructed and demonstrated for this purpose. The second investigation involved the evaluation of four commercially available RF leak detectors. These are hand-held units that operate in the 10 kHz - 462.6 MHz frequency range. They are used to search for localized leaks in shelter shielding.

In the area of long-term outdoor exposure, a comprehensive five-year program was carried out in which thirty-two 4 x 8 ft (1.1 x 2.2 m) shelter panels were subjected to outdoor weathering at the U.S. Army Tropic Test Center in Panama. Periodic visits were made to this location to cut these panels into a variety of different types of specimens for testing to determine whether the tropic exposure caused any degradation in property levels.

In the area of testing techniques, two investigations were performed to evaluate the suitability of using the floating roller and climbing drum peel tests to characterize adhesive bonding in shelter constructions. Several shortcomings in these current ASTM test procedures were addressed.

In the area of repair, an effort was undertaken to implement a previously developed shelter repair kit into the DOD inventory so that users of tactical shelters could carry out several types of field repair. In the area of redeployment, two projects were carried out. The first involved the design, fabrication, and demonstration of a prototype hardware system applicable to S-280 shelters. The purpose of the system was to provide a means of airlifting a heavily damaged S-280 shelter. The second effort consisted of a feasibility study to apply this same technology to the much larger and heavier ISO shelter.

General support activities included participation in ASTM E6.53 subcommittee activities. This subcommittee is responsible for developing standard practices and specifications for processes and materials used in shelter manufacturing and repair. In addition to this, the University prepared and analyzed the results of a survey that was

distributed throughout the shelter community. The purpose was to collect information that would serve to focus future R&D activities on issues of significant benefit to shelter manufacturers and users.

3. MATERIALS TESTING AND EVALUATION

A large variety of materials and processes are used in the construction and repair of tactical shelters. The government and various shelter manufacturers have undertaken some materials screening investigations prior to the selection of specific materials for use in shelter construction. However, as new materials become available, old formulations are slightly modified, or new specification requirements are established, additional testing is regularly required to insure that materials and processes used in shelter construction or repair meet the necessary property requirements. Many test and evaluation projects related to this subject area were undertaken during this program and are described in the succeeding paragraphs.

3.1 Testing of Structural Film Adhesives for Shelter Sandwich Panels

A task was conducted to qualify three structural film adhesive candidates to ASTM E865, "Structural Film Adhesives for Honeycomb Sandwich Panels." This specification is the controlling adhesive material document used in construction of honeycomb portable tactical shelter buildings for DOD. Three adhesive candidates were identified by the DOD Project Engineer. These adhesives are: R382-3 from Ciba Geigy, NB 101 from Newport, and MA 429T from McCann. Two of these adhesives, R382-3 and NB 101, were previously qualified, but requalification is required according to the specification. These two adhesives were being used in production at one of the major manufacturers of shelters for DOD. Samples of these adhesives were obtained from both the shelter manufacturer and the adhesive manufacturer. The remaining adhesive, MA 429T, was obtained from the adhesive manufacturer only. Table 1 lists the tests conducted according to ASTM E865.

The metal used for all adhesively bonded test specimens was 5052 H34 bare aluminum. This aluminum is commonly used in shelter construction. Two aluminum surface preparations are currently approved for shelter construction; optimized FPL etch (OFPL) and P2. The use and chemical composition of each is designated in ASTM E864, "Surface Preparation of Aluminum Alloys to be Adhesively Bonded in Honeycomb Shelter Panels." After etching, all the aluminum test specimens were primed with BR-127 adhesive primer.

The test specimens were prepared and tested in accordance with ASTM E865. The results obtained are shown in Table 2. The three adhesive candidates met the

TABLE 1

PHYSICAL REQUIREMENTS FOR THE FILM ADHESIVE PER ASTM E865

Test	Requirement
Normal-temperature shear, psi (MPa)	2903 (20)
High-temperature shear, psi (MPa)	
140°F (60°C)	2903 (20)
199°F (90°C)	1888 (13)
Low-temperature shear, psi (MPa)	2175 (15)
Humidity exposure, psi (MPa)	723 (5)
Salt spray exposure, psi (MPa)	2322 (16)
Dead load stress durability, hrs:	
40% of 140°F (60°C) failure stress	40
30% of 140°F (60°C) failure stress	540
20% of 140°F (60°C) failure stress	1500

TABLE 2

LAP SHEAR PROPERTIES FOR STRUCTURAL FILM ADHESIVES

Test, Test Temperature and Minimum Strength Requirement	Film Adhesive:	R382-3				NB 101				MA429T	
	Source:	Ciba Geigy		Brunswick		Newport		Brunswick		McCann	
	Surface Prep.:	OFPL	P2	OFPL	P2	OFPL	P2	OFPL	P2	OFPL	P2
R.T. Shear (2903 MPa)		4310	4320	4590	4260	4190	4130	4420	3870	3920	3840
-67°F Shear (2175 MPa)		3340	3570	3280	3820	3780	3770	3110	3000	3500	3300
140°F Shear (2903 MPa)		4140	4200	4240	3950	4350	4190	4120	3670	4050	3970
199°F Shear (1888 MPa)		3350	3650	3680	3660	3770	3800	3500	3020	3800	3500
After Humidity (723 MPa)		2500	2020	2850	2310	2650	1760	1680	1300	2630	2870
Salt Spray (2322 MPa)		4020	3970	4140	3910	3990	3530	3970	4440	4070	4330
Stress Durability Aging[1] 40% Stress Level (40 hr)		3860	3580	3830	4190	4100	3970	4290	4110	3890	3050
Stress Durability Aging[1] 30% Stress Level (540 hr)		3730	3780	3630	3470	3940	3710	3800 ****	3830	4050	4110
Stress Durability Aging[1] 20% Stress Level (1500 hr)		3420	3100	3570	3610	3450 *	3180	3490 **	3270	3920	3920

[1] Stress durability results are residual strengths.
Agings are done at 140°F, 95 ± 5% relative humidity

* 1 S/D Failure
** 2 Failures in S/D
**** 4 S/D Failures

minimum requirements of the specification. Based upon these results, no difference was observed between the OFPL and P2 etches.

3.2 Qualification of Kraft Paper Honeycomb Core

A task was conducted to qualify Kraft paper honeycomb core to ASTM E1091, "Specification for Non-Metallic Honeycomb Core for Use in Shelter Panels." This honeycomb core is manufactured by Hexagon Honeycomb Corp. in St. Louis, Missouri. In the initial qualification tests, the honeycomb core repeatably failed to meet the minimum values for compression tests. The honeycomb core manufacturer was notified and new samples were submitted. The results obtained from this sample are shown in Table 3. All of the values obtained meet the requirements in the specification.

3.3 Evaluation of Honeycomb Sandwich Panels and Adhesive Peel Specimens

Honeycomb sandwich panels and adhesive peel specimens were received along with a request to perform several specific tests. All tests were completed and a test report was prepared and forwarded to WL/MLSE, STRNC-UST, and ESD/AVMS. The test report included all data and photographs of the test set-up and specimens before and after test. All of the data measured exceeded the requirements set in the appropriate specification. The following tests were performed in accordance with the noted specifications.

- Testing of honeycomb sandwich panels.
  - Visual inspection as described in Paragraph 10.6.1 of ASTM E874.
  - Dimensional and flatness inspection and testing described in Paragraph 10.6.2 of ASTM E874.
  - Tap test as described in Paragraph 10.6.3 of ASTM E874.
  - Climbing drum peel test in accordance with Paragraph 10.2.1.1 of ASTM E874 and ASTM D1781, minimum average climbing drum peel strength shall be 6.9 lbsF/inch width (12.1 N/cm width).
  - Flatwise tension in accordance with Paragraph 10.2.1.2 of ASTM E874 and ASTM C297, minimum average flatwise tensile strength shall be 306 psi (2.10 MPa).

TABLE 3

HONEYCOMB CORE MATERIAL PROPERTIES, ASTM E-1091

Material Property	Requirement	Test Results
Maximum density, lb/ft^3 (Kg/m^3)	4.4 (70.6)	4.0 (64.2)
Compression strength[a], psi (MPa)		
Dry, minimum[b]	404 (2.78)	586 (4.04)
Wet, minimum[c]	163 (1.12)	312 (2.15)
At elevated temperature[d]	185 (1.27)	454 (3.13)
Cyclic aging, minimum	119 (0.82)	440 (3.03)
Shear strength[a], psi (MPa)		
Dry, minimum		
L direction[b]	180 (1.24)	241 (1.66)
W direction[b]	113 (0.78)	158 (1.09)
Wet, minimum		
L direction[c]	86 (0.59)	176 (1.21)
W direction[c]	58 (0.40)	89 (0.61)
Brittleness/Impact		
Drop height, minimum, inch (cm)	30 (76.2)	(f)
Flatwise tensile, minimum[e], psi (MPa)	306 (2.11)	531 (3.66)
Water migration resistance		
24 hours, maximum, no. of cells	3	0.63

NOTES:

a. Two-inch (51 mm) thick core with 0.05 inch (1.3 mm) facings, tested at 73 ± 2°F (22.7 ± 1°C) unless otherwise stated herein.

b. At equilibrium with 73 ± 2°F (22.7 ± 1°C), and 50 ± 4 percent R.H.

c. After soaking in water at 70 ± 5°F (21.1 ± 3°C) for 48 hours with perforated facings.

d. After heating for 30 mins. at, and tested at, 176 ± 5°F (80 ± 3°C).

e. Tested at 73 ± 2°F (22.7 ± 1°C) with loading blocks bonded directly to each side of core specimen having a minimum area of 9 in^2 (5806 mm^2).

f. Brittleness Impact will be determined by U.S. Army Natick Research, Engineering, and Development Center.

- Testing of floating roller peel specimens.
    - Structural floating roller peel test in accordance with Paragraph 5.8 of ASTM E865 and ASTM D3187, minimum average floating roller peel strength shall be 25.1 lbsF/inch width (44.0 N/cm width).

3.4 Evaluation of Foam Sandwich Panels, Adhesive Bonded Tensile Lap Shear Specimens, and Foam Core Plate Shear

A project to evaluate foam cores and adhesives, which are candidates for shelter construction, was initiated and completed. Three different foam materials were included in the testing but the designations of the foams were not provided. Each was received from a different shelter manufacturer, who in turn, had procured it from the foam manufacturer. The foam core was tested in flatwise tension, compression, and plate shear. The adhesive was tested in tensile lap shear at -65°F, R.T., and 200°F.

Some of the foam core samples had flatwise tensile strengths that were below the minimum standards set for shelter construction. Several retests were run and while most of the samples of one type foam core continued to fail, some did meet or slightly exceed the minimum standards. It appears that one of the tested cores is somewhat brittle and if only slight misalignment in the test setup or some other very slight anomaly occurs, premature failure results. As a result of these tests, that particular foam core manufacturer reformulated the foam to increase toughness. All other candidate materials and test results exceeded the minimum standards for shelter construction.

3.5 Evaluation of Low VOC Primers for Adhesively Bonded Honeycomb Shelter Panels

A project was conducted to evaluate low VOC adhesive primers for honeycomb shelter panel construction and/or repair. The adhesive primer currently used for all honeycomb shelter construction and repair is solvent-based and contains 800 g/l (grams/liter) VOC. The U.S. Air Force and U.S. Army Repair Depots are in Sacramento County, CA, where State and Federal regulations require the VOC limit to be 340 g/l. Not all, but many of the shelters repaired at the depots are honeycomb construction and require an adhesive primer. Most original honeycomb shelter construction does not occur in California. These operations are located in states having less stringent requirements for VOC emissions. However, if those states would lower their VOC

requirements, there is "no" other adhesive primer qualified to the controlling specification, whether it be high or low VOC. The controlling specification is ASTM E866, "Corrosion-Inhibiting Adhesive Primer for Aluminum Alloys to be Adhesively Bonded in Honeycomb Shelter Panels."

UDRI conducted a survey of the adhesive industry for primers which have VOC less than 340 g/l. Four candidates were identified and are listed in Table 4. Also included in the table is the currently used solvent base primer, BR-127. Tests were conducted on this primer for baseline data. Two American Cyanamid low VOC primers were identified; one chromated and one non-chromated. Both of these were included in the study. In the future, chromated vs. non-chromated may become an issue. Two 3M low VOC primers were also identified. One is a two-part version of the other and was not included in the study. The two-part version does have the advantage of extended shelf life.

The material and procedures used are those which are normally used in shelter construction and are listed in Table 5. The cure cycle used for BR-127 is that recommended by the controlling specification. The cure cycles used for the low VOC primers were those recommended by the manufacturers.

The controlling specification, ASTM E866, requires that tests be performed on cured primer film and mechanical properties determined using adhesive bonded panels. Generally the determination of primer film properties involve coating aluminum with primer and exposing it to various environments. Tests then include pencil hardness and/or visual inspection for cracks, blisters, loss of adhesion, and corrosion. The results obtained are shown in Tables 6 to 12. All of the primers met the requirements in the specification.

The mechanical property tests include tensile lap shear and floating roller peel at various temperatures and/or after varying exposure conditions. In general, the results obtained from specimens prepared with the water base (low VOC) primers are lower than those obtained using the solvent base primer but do exceed the requirements in the specification. One exception may be the tensile lap shear strength at 200°F after 2 weeks at 200°F and 95-100% R.H. The results obtained were slightly lower or slightly higher than the minimum requirement in the specification. This is not to say that water base primers are not suitable for shelter construction. However, if consideration is given

TABLE 4

PHYSICAL CHARACTERISTICS OF ADHESIVE PRIMERS

Primer	Source	VOC, g/l	% Solids	Corrosion Inhibitor	Shelf Life
BR-127	American Cyanamid	800	10	Chromated	6 mos. @ 0°F (-18°C)
BXR250-WBP	American Cyanamid	200	20	Chromated	? @ 40°F (4°C) (1)
BXR250-WBP-NC	American Cyanamid	200	20	Non-chromated	? @ 40°F (4°C) (1)
EC 3982	3M	112	20	Chromated	90 days @ 40°F (4°C)
EC 3993B/A	3M	170	20	Chromated	6 mos. @ 40°F(4°C) (2)

NOTES:

1. From American Cyanamid data sheet. "For long term storage, the primer should be stored at 40°F (4°C)."
2. EC 3993B/A is a two-part version of EC 3982 and was not included in this study.

TABLE 5
MATERIALS USED IN EVALUATION OF LOW VOC PRIMERS

ALUMINUM ALLOY:	6061-T6 Aluminum Surface Preparation, OFPL Etch
ADHESIVE:	Ciba Geigy R-382
PRIMERS:	BR-127, American Cyanamid BXR 250-WBP, American Cyanamid BXR 250-WBP-NC, American Cyanamid EC 3982, 3M

CONTROLLING SPECIFICATION:

ASTM E866, "Corrosion-Inhibiting Adhesive Primer for Aluminum Alloys to be Adhesively Bonded in Honeycomb Shelter Panels"

TABLE 6

PENCIL HARDNESS OF CURED PRIMER FILM PER ASTM E866 PARAGRAPH 5.2.3

Adhesive Primer			
BR-172	EC 3982	BXR 250-WBP	BXR 250-WBP-NC
>9H	9H	>9H	9H

NOTES:

1. Pencil hardness requirement, 4H minimum.
2. BR-127 primer cured per E866, air dry 30 minutes and at 239° ± 9°F (115±5°C) for 75 to 90 minutes.
3. EC 3982, BXR 250-WBP, and BXR 250-WBP-NC primers cured per manufacturer's recommendation, air dry 30 minutes and at 250°F (121°C) for 60 minutes.

TABLE 7

WATER RESISTANCE OF CURED PRIMER FILM PER ASTM E866 PARAGRAPH 5.2.5

	Adhesive Primer			
Test	BR-127	EC 3982	BXR250-WBP	BXR250-WBP-NC
Pencil Hardness	>9H	9H	>9H	>9H
Blistering	none	none	none	none
Cracking	none	none	none	none
Loss of Adhesion	none	none	none	none

NOTES:

1. Water resistance, immerse in distilled water for 7 days at 75° ± 5°F (24±3°C) and then exposed to 100% R.H. at 121° ± 5°F (49±3°C) for 30 days.
2. Pencil hardness requirement, 4H minimum.
3. Physical requirements, no blistering, cracking, or loss of adhesion.
4. BR-127 primer cured per E866, air dry 30 minutes and at 239° ± 9°F (115±5°C) for 75 to 90 minutes.
5. EC 3982, BXR250-WBP, and BXR250-WBP-NC primers cured per manufacturer's recommendation, air dry 30 minutes and at 250°F (121°C) for 60 minutes.

TABLE 8

HEAT RESISTANCE OF CURED PRIMER FILM PER ASTM E866 PARAGRAPH 5.2.6

Test	Adhesive Primer			
	BR-127	EC 3982	BXR250-WBP	BXR250-WBP-NC
Pencil Hardness	>9H	>9H	>9H	>9H
Blistering	none	none	none	none
Cracking	none	none	none	none
Loss of Adhesion	none	none	none	none

NOTES:

1. Heat resistance, heat at 249° ± 5°F (121 ± 3°C) for 70 hours.
2. Pencil hardness requirement, 4H minimum.
3. Physical requirements, no blistering, cracking, or loss of adhesion.
4. BR-127 primer cured per E866, air dry 30 minutes and at 239° ± 9°F (115 ± 5°C) for 75 to 90 minutes.
5. EC 3982, BXR250-WBP, and BXR250-WBP-NC primers cured per manufacturer's recommendation, air dry 30 minutes and at 250°F (121°C) for 60 minutes.

TABLE 9

LOW TEMPERATURE SHOCK OF CURED PRIMER FILM PER ASTM E866 PARAGRAPH 5.2.7

Test	Adhesive Primer			
	BR-127	EC 3982	BXR250-WBP	BXR250-WBP-NC
Blistering	none	none	none	none
Cracking	none	none	none	none
Loss of Adhesion	none	none	none	none

NOTES:

1. Low temperature shock, 24 cycles each consisting of 25 minutes at 150 ± 5°F (66 ± 3°C) then, transfer in 5 seconds to -66° ± 5°F (-54 ± 5°C) for 5 minutes. Last cycle at -66°F (-54°C) shall be 5 hours.
2. Physical requirements, no blistering, cracking, or loss of adhesion.
3. BR-127 primer cured per E866, air dry 30 minutes and at 239° ± 9°F (115 ± 5°C) for 75 to 90 minutes.
4. EC 3982, BXR250-WBP, and BXR250-WBP-NC primers cured per manufacturer's recommendation, air dry 30 minutes and at 250°F (121°C) for 60 mins.

TABLE 10

CORROSION RESISTANCE OF CURED PRIMER FILM PER ASTM E866 PARAGRAPH 5.2.8

Test	Adhesive Primer			
	BR-127	EC 3982	BXR250-WBP	BXR250-WBP-NC
Blistering	none	none	none	none
Cracking	none	none	none	none
Loss of Adhesion	none	none	none	none

NOTES:

1. Corrosion resistance, 5% salt fog in accordance with B117 for 40 days.
2. Physical requirements, no blistering or cracking.
3. No substrate degradation more than 3 mm from scribe mark.
4. BR-127 primer cured per E866, air dry 30 minutes and at 239° ± 9°F (115 ± 5°C) for 75 to 90 minutes.
5. EC 3982, BXR250-WBP, and BXR250-WBP-NC primers cured per manufacturer's recommendation, air dry 30 minutes and at 250°F (121°C) for 60 mins.

TABLE 11

HUMIDITY AGING OF CURED PRIMER FILM PER ASTM E866 PARAGRAPH 5.2.9

Test	Adhesive Primer			
	BR-127	EC 3982	BXR250-WBP	BXR250-WBP-NC
Blistering	none	none	none	none
Cracking	none	none	none	none
Loss of Adhesion	none	none	none	none

NOTES:

1. Humidity aging, 30 days at 121° ± 5°F (49 ± 3°C) and 100% R.H.
2. Physical requirements, no blistering, cracking, or loss of adhesion.
3. BR-127 primer cured per E866, air dry 30 minutes and at 239° ± 9°F (115 ± 5°C) for 75 to 90 minutes.
4. EC 3982, BXR250-WBP, and BXR250-WBP-NC primers cured per manufacturer's recommendation, air dry 30 minutes and at 250°F (121°C) for 60 mins.

TABLE 12

LOSS OF ADHESION OF CURED PRIMER FILM PER
ASTM E866 PARAGRAPH 5.2.10

Adhesive Primer			
BR-127	EC 3982	BXR250-WBP	BXR250-WBP-NC
none	none	none	none

NOTES:

1. No primer shall be removed from the panel, other than that removed by scribing.

2. BR-127 primer cured per E866, air dry 30 minutes and at 239° ± 9°F (115 ± 5°C) for 75 to 90 minutes.

3. EC 3982, BXR250-WBP, and BXR250-WBP-NC primers cured per manufacturer's recommendation, air dry 30 minutes and at 250°F (121°C) for 60 minutes.

to low VOC water base primers for shelter construction, further examination under hot-wet conditions should be conducted. The conditions may have to be relaxed or the requirement lowered. The results obtained are listed in Tables 13 to 19.

Another requirement in the specification is that the primer be sprayable. Although the conditions are different, all the water base primers are sprayable. Because the primary solvent is water and does not evaporate rapidly, the spray must contain more air and less primer. This requires higher air pressures, about 30 psi (0.2 MPa) compared to 10 psi (0.07 MPa) for solvent based primers. When higher air pressures are used, the primer film applied is nearly dry upon contact. Also the specification requires the primer to contain 10% solids. All the low VOC water base primers tested have 20% solids.

3.6 Analysis of Production Honeycomb Sandwich Panels

Recently, during the manufacture of production roof panels for tactical shelters, several panels debonded immediately upon removal from the bonding press. Representatives from UDRI, WL/MLSE, and U.S. Army Natick R&D visited the production facility to lend assistance in determining the cause for debonding. Several tests including flatwise tension in areas adjacent to the debond area were performed at the production facility but did not reveal the cause. The debonds occurred between the structural adhesive layer and the honeycomb core. It has been agreed that the most probable cause was the adhesive, possibly improper mixing or insufficient quantity of resin catalyst. However, the shelter manufacturer changed adhesive systems until the problem was resolved. After that, additional roof panels debonded. All debonded panels have been shelter roof panels. The only known difference in the roof panels from the side or floor panels is the addition of a 1-inch thick piece of closed cell foam inserted in the honeycomb core for insulation.

A 1 ft. x 1 ft. x 1 inch (30.5 cm x 30.5 cm x 2.54 cm) piece of foam was weighed, then placed into an oven at 270°F (132°C) for 35 minutes. This heat cycle is similar to that used in the construction of shelter panels. It was hoped that if any materials were driven off, a weight loss could be measured. However, the apparent outgassing was so great that the block of foam had broken into many pieces, making it impossible to determine weight loss. The test was repeated and the results were the same. These results were discussed with the manufacturer and it was suggested that the same results may occur with other "closed cell" foam, in particular if the sample size was large. The test was once again repeated, but the 1-ft. (30.5-cm) square block of foam

TABLE 13

NORMAL TEMPERATURE SHEAR STRENGTH, 76° ± 5°F (24 ± 3°C), PER ASTM E866, PARAGRAPH 5.3.2

Adhesive Primer	Shear Strength, psi (MPa)
BR-127	4723 (32.5)
EC 3982	5661 (39.0)
BXR250-WBP	4196 (28.9)
BXR250-WBP-NC	4020 (27.7)

NOTES:

1. BR-127 primer cured per E866, air dry 30 minutes and at 239° ± 9°F (115 ± 5°C) for 75 to 90 minutes.
2. EC 3982, BXR250-WBP, and BXR250-WBP-NC primers cured per manufacturer's recommendation, air dry 30 minutes and at 250°F (121°C) for 60 minutes.
3. Bonding adhesive, Ciba-Geigy R-382, cured at 275° ± 5°F (133 ± 3°C) for 35 to 40 minutes under 30 psi (0.21 MPa).
4. Test procedure and specimen per ASTM D1002, aluminum alloy 0.064 inch (1.6 mm) thick 6061-T6. Surface preparation OFPL etch per ASTM E864.
5. Minimum requirement per ASTM E866, 2900 psi (20 MPa).

TABLE 14

LOW TEMPERATURE SHEAR STRENGTH, -66° ± 5°F (-54 ± 3°C), PER ASTM E866, PARAGRAPH 5.3.3

Adhesive Primer	Shear Strength, psi (MPa)
BR-127	4102 (28.3)
EC 3982	4230 (29.1)
BXR250-WBP	3695 (25.5)
BXR250-WBP-NC	3381 (23.3)

NOTES:

1. BR-127 primer cured per E866, air dry 30 minutes and at 239° ± 9°F (115 ± 5°C) for 75 to 90 minutes.
2. EC 3982, BXR250-WBP, and BXR250-WBP-NC primers cured per manufacturer's recommendation, air dry 30 minutes and at 250°F (121°C) for 60 minutes.
3. Bonding adhesive, Ciba-Geigy R-382, cured at 275° ± 5°F (133 ± 3°C) for 35 to 40 minutes under 30 psi (0.21 MPa).
4. Test procedure and specimen per ASTM D1002, aluminum alloy 0.064 (1.6 mm) inch thick 6061-T6. Surface preparation OFPL etch per ASTM E864.
5. Minimum requirement per ASTM E866, 2900 psi (20 MPa).

TABLE 15

HIGH TEMPERATURE SHEAR STRENGTH, 200° ± 5°F (93 ± 3°C), PER ASTM E866, PARAGRAPH 5.3.4

Adhesive Primer	Shear Strength, psi (MPa)
BR-127	4333 (29.9)
EC 3982	4124 (28.4)
BXR250-WBP	3995 (27.5)
BXR250-WBP-NC	3650 (25.1)

NOTES:

1. BR-127 primer cured per E866, air dry 30 minutes and at 239° ± 9°F (115 ± 5°C) for 75 to 90 minutes.
2. EC 3982, BXR250-WBP, and BXR250-WBP-NC primers cured per manufacturer's recommendation, air dry 30 minutes and at 250°F (121°C) for 60 minutes.
3. Bonding adhesive, Ciba-Geigy R-382, cured at 275° ± 5°F (133 ± 3°C) for 35 to 40 minutes under 30 psi (0.21 MPa).
4. Test procedure and specimen per ASTM D1002, aluminum alloy 0.064 inch (1.6 mm) thick 6061-T6. Surface preparation OFPL etch per ASTM E864.
5. Minimum requirement per ASTM E866, 1890 psi (13.0 MPa).

TABLE 16

HUMIDITY EXPOSURE-SHEAR STRENGTH AT 200° ± 5°F (93 ± 3°C)
AFTER 2 WEEKS AT 200° ± 5°F (93 ± 3°C) AND 95 ± 5% R.H.
PER ASTM E866, PARAGRAPH 5.3.5

Adhesive Primer	Shear Strength, psi (MPa)	
BR-127	1047 (7.2)	
EC 3982	800 (5.5)	523 (3.6) (6)
BXR250-WBP	717 (4.9)	588 (4.1) (6)
BXR250-WBP-NC	797 (5.5)	600 (4.1) (6)

NOTES:

1. BR-127 primer cured per E866, air dry 30 minutes and at 239° ± 9°F (115 ± 5°C) for 75 to 90 minutes.
2. EC 3982, BXR250-WBP, and BXR250-WBP-NC primers cured per manufacturer's recommendation, air dry 30 minutes and at 250°F (121°C) for 60 mins.
3. Bonding adhesive, Ciba-Geigy R-382, cured at 275° ± 5°F (133 ± 3°C) for 35 to 40 minutes under 30 psi (0.21 MPa).
4. Test procedure and specimen per ASTM D1002, aluminum alloy 0.064 inch (1.6 mm) thick 6061-T6. Surface preparation OFPL etch per ASTM E864.
5. Minimum requirement per ASTM E866, 725 psi (5.0 MPa).
6. Rerun data.

TABLE 17

SALT SPRAY-SHEAR STRENGTH AT 76° ± 5°F (24 ± 3°C)
AFTER 2 WEEKS EXPOSURE TO 5% SALT FOG AT
95° ± 5°F (35 ± 3°C) PER ASTM E866, PARAGRAPH 5.3.6

Adhesive Primer	Shear Strength, psi (MPa)
BR-127	4484 (30.9)
EC 3982	3826 (26.4)
BXR250-WBP	3617 (24.9)
BXR250-WBP-NC	3635 (25.0)

NOTES:

1. BR-127 primer cured per E866, air dry 30 minutes and at 239° ± 9°F (115 ± 5°C) for 75 to 90 minutes.

2. EC 3982, BXR250-WBP, and BXR250-WBP-NC primers cured per manufacturer's recommendation, air dry 30 minutes and at 250°F (121°C) for 60 minutes.

3. Bonding adhesive, Ciba-Geigy R-382, cured at 275° ± 5°F (133 ± 3°C) for 35 to 40 minutes under 30 psi (0.21 MPa).

4. Test procedure and specimen per ASTM D1002, aluminum alloy 0.064 inch (1.6 mm) thick 6061-T6. Surface preparation OFPL etch per ASTM E864.

5. Minimum requirement per ASTM E866, 2390 psi (16.5 MPa).

TABLE 18

NORMAL TEMPERATURE METAL-TO-METAL PEEL STRENGTH, 75° ± 5°F (24 ± 3°C), PER ASTM E866, PARAGRAPH 5.3.7

Adhesive Primer	Peel Strength, lbf/in (N/cm)
BR-127	49.4 (86.5)
EC 3982	50.5 (88.4)
BXR250-WBP	37.4 (65.5)
BXR250-WBP-NC	36.9 (64.6)
None	44.9 (78.6)

NOTES:

1. BR-127 primer cured per E866, air dry 30 minutes and at 239° ± 9°F (115 ± 5°C) for 75 to 90 minutes.

2. EC 3982, BXR250-WBP, and BXR250-WBP-NC primers cured per manufacturer's recommendation, air dry 30 minutes and at 250°F (121°C) for 60 minutes.

3. Bonding adhesive, Ciba-Geigy R-382, cured at 275° ± 5°F (133 ± 3°C) for 35 to 40 minutes under 30 psi (0.21 MPa).

4. Test procedure and specimen per ASTM D1002, aluminum alloy 0.064 inch (1.6 mm) thick 6061-T6. Surface preparation OFPL etch per ASTM E864.

5. Minimum requirement per ASTM E866, 25.1 lbf/in (44 N/cm).

TABLE 19

LOW TEMPERATURE PEEL STRENGTH, -66° ± 5°F (-54 ± 3°C), PER ASTM E866, PARAGRAPH 5.3.8

Adhesive Primer	Peel Strength, lbf/in (N/cm)
BR-127	24.5 (42.9)
EC 3982	20.8 (36.4)
BXR250-WBP	Being Rerun
BXR250-WBP-NC	Being Rerun
None	26.6 (46.6)

NOTES:

1. BR-127 primer cured per E866, air dry 30 minutes and at 239° ± 9°F (115 ± 5°C) for 75 to 90 minutes.

2. EC 3982, BXR250-WBP, and BXR250-WBP-NC primers cured per manufacturer's recommendation, air dry 30 minutes and at 250°F (121°C) for 60 minutes.

3. Bonding adhesive, Ciba-Geigy R-382, cured at 275° ± 5°F (133 ± 3°C) for 35 to 40 minutes under 30 psi (0.21 MPa).

4. Test procedure and specimen per ASTM D1002, aluminum alloy 0.064 inch (1.6 mm) thick 6061-T6. Surface preparation OFPL etch per ASTM E864.

5. Minimum requirement per ASTM E866, 15.0 lbf/in (26.3 N/cm).

was first pushed through the same type of honeycomb core used in shelter construction. The hexagonally-shaped pieces were then weighed and subjected to the same heat cycle. Afterwards the weight loss was determined to be 11.8%. Although the method of determining weight loss may be crude, it does appear that a significant amount of weight loss occurs.

Due to the significant quantity of apparent weight loss due to outgassing, a sample of foam was subjected to the same heat cycle and the outgassing products were analyzed using gas chromatography. Figure 1 illustrates the outgassing for 25 minutes of the heat cycle. All of the peaks have been identified, but the most significant is the first which is illustrated in Figure 2. This peak represents Freon being outgassed, most of which is released between 2 and 4 minutes into the heat cycle. During construction of the sandwich panels, the pressure is momentarily released after about 1 minute to allow for outgassing. It may be possible that a significant amount of Freon could be trapped in the panel during manufacture and may contribute to debonding.

3.7 Shelter Foam Insulation

As discussed in Section 3.6, a shelter manufacturer was having difficulty with roof panels debonding immediately after cure. UDRI, WL/MLSE, and U.S. Army Natick Laboratories tried to assist in determining the cause, but could only speculate. However, since all of the panels which debonded were for the shelter roof, UDRI obtained a sample of the insulating foam used in roof panels only. Gas chromatograms indicated a significant amount of residual Freon in the foam. Since that time the manufacturer has changed the process slightly and asked that a new sample be analyzed. Gas chromatography indicates that the amount of residual freon has been reduced by a factor of 2.3 as shown in Table 20. It is difficult to determine the volume of Freon but the relative abundance can be determined. Figure 3 illustrates these gas chromatograms. It is still not certain whether or not this was the cause of debonding in the roof panels.

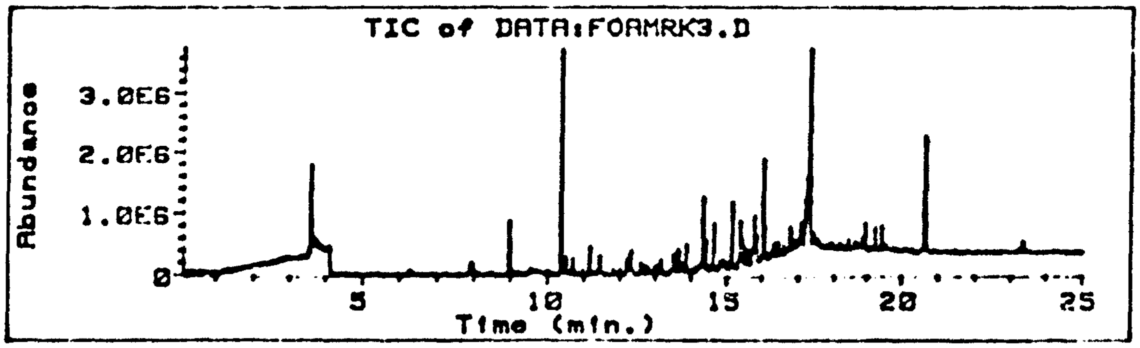


Figure 1. Gas Chromatograph of Outgassing of Foam During Sandwich Panel Heat Cycle.

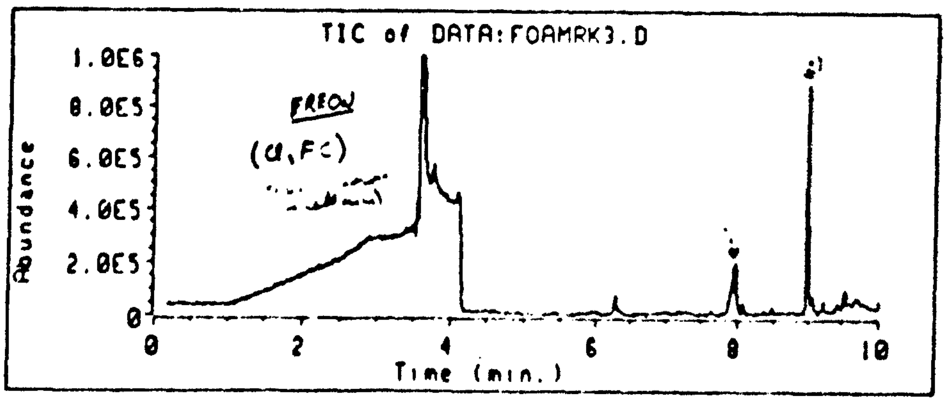


Figure 2. Gas Chromatograph Indicating Significant Loss of Freon Between 2 and 4 Minutes of Heat Cycle.

TABLE 20

RELATIVE ABUNDANCE OF FREON IN INSULATING FOAM SAMPLES

Sample	Data File No.	Relative Abundance of Freon
Original	202.D	4.57
New Foam	203.D	1.95

3.8 Post Test Analysis of Hardened Shelter

An experimental hardened shelter was subjected to a simulated nuclear test. Some unexpected damage occurred during the test. Representatives from UDRI, WL/MLSE, and U.S. Army Natick R&D met to examine the shelter and determine if UDRI could lend assistance in post-test analysis. After reviewing the movies of the test and examination of shelter, it was the opinion of both the UDRI and WL/MLSE representatives that the damage was caused by a design flaw rather than materials selection or processing technique. Small pieces of the lower shell assembly were cut out and returned to UDRI for analysis.

Flatwise tension specimens were cut from the lower assembly in two areas. One contained 3.8 lbs/ft^3 (61 Kg/m^3) core and one 2.5 lbs/ft^3 (40 Kg/m^3) core. Both cores were Kraft paper. Both samples exceeded the minimum flatwise tensile strength value given in the materials specification. It was noted that the 2.5 lb/ft^3 (40 Kg/m^3) core did have some "wrinkling," although it did not seem to affect tensile properties. Flatwise compression properties were then determined for the 2.5 lb/ft^3 (40 Kg/m^3) core. These results did not meet the minimum value in the materials specification. It is not known if the wrinkling was caused by the processing of the assembly or during the test. The results obtained are shown in Table 21.

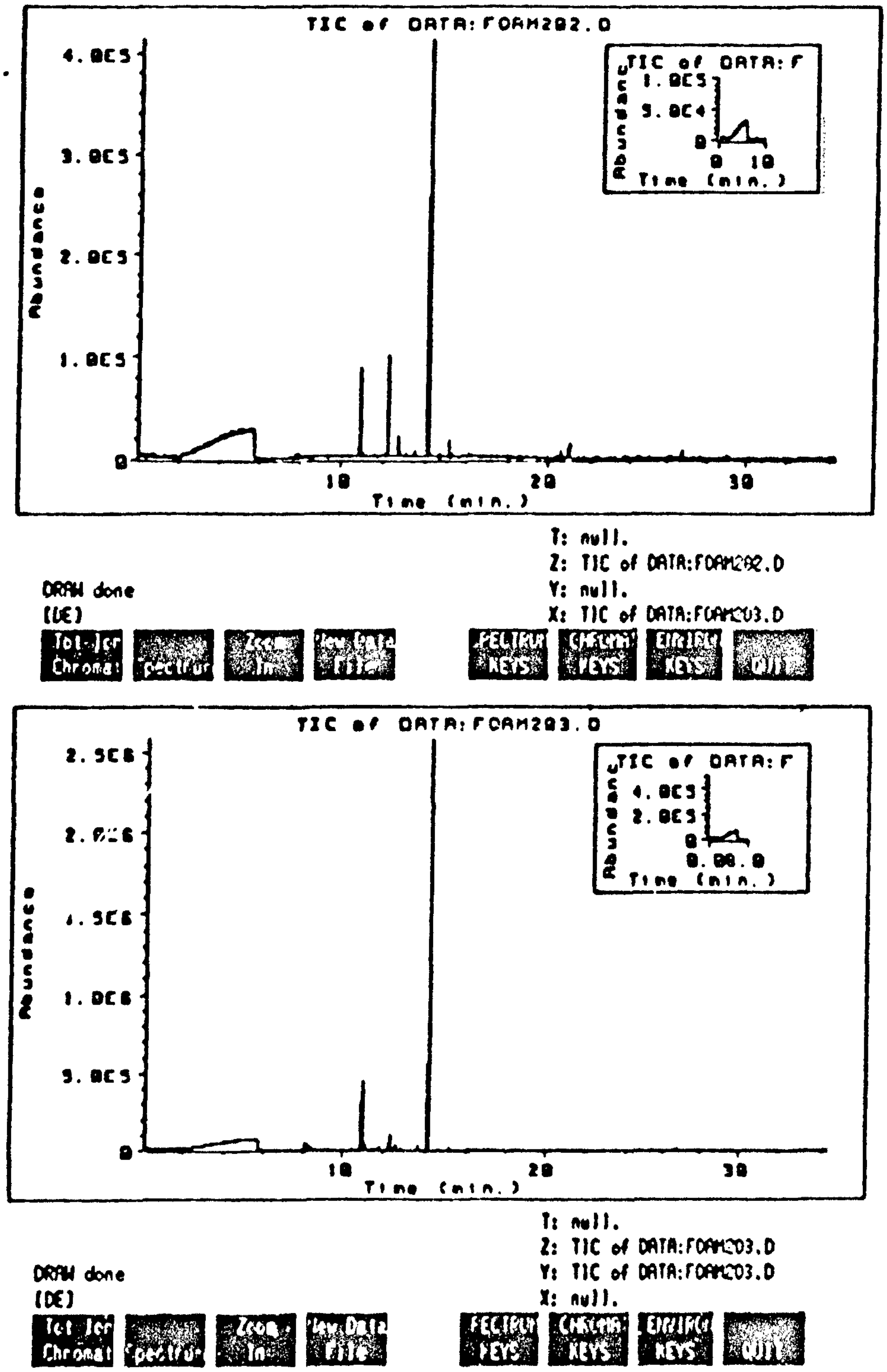


Figure 3. Gas Chromatograms of Insulating Foam in Shelter Roof Panels.

TABLE 21

HONEYCOMB SANDWICH PROPERTIES FROM LOWER SHELL ASSEMBLY

Material Property	Core Density, lbs/ft^3(Kg/m^3)	Ultimate Strength psi (MPa)	Min. Requirement psi (MPa)
Tension	3.8 (61)	408 (2.8)	306 (2.1)
Tension	2.5 (40)	260 (1.8)	231 (1.6)
Compression	2.5 (40)	182 (1.3)	232 (1.6)

3.9 Structural Film Adhesive Qualification

Several structural film adhesives had previously been qualified to ASTM E865 by UDRI. The manufacturer of one of these candidates made a slight change in the formulation. This change is the percent of a dye which is added to the catalyst which in turn is added to the epoxy adhesive. This dye is a visual aid to insure that proper quantities are used and mixing of both parts occur during application to the scrim during adhesive film production. Although this structural film adhesive had previously been qualified, requalification was required on the new formulation containing additional dye.

Testing was carried out and the data are shown in Table 22. The tensile lap shear after humidity exposure failed to meet the minimum requirements in the specification. Several retests were conducted, but all failed the requirement. At this time testing was suspended and the adhesive manufacturer was notified. Other samples were promised, but none arrived.

During the requalification testing at UDRI, one of the shelter manufacturers was having difficulty with the same adhesive. The shelter manufacturer is required to fabricate daily test panels to insure that the materials and processes used meet or exceed the requirements in the procurement document. One of these daily test panels failed, putting 62 constructed shelter panels in jeopardy of being rejected. UDRI assisted the shelter manufacturer and the U.S. Army Natick Laboratories in a test plan to save as many of the 62 panels as possible.

Besides devising a test plan (to be conducted by the shelter manufacturer) that might save the otherwise rejected panels, some evaluation was performed at UDRI on the lot of adhesive (No. 965) used in the manufacture of the daily test panel. Samples from three rolls were returned to UDRI for test. Tensile lap shear after humidity aging,

TABLE 22

STRUCTURAL FILM ADHESIVE PROPERTIES,
ASTM E865

Test	Requirement	Test Results(1)
Film weight, lb/ft^2 (kg/m^2)		0.103 (0.503)
Normal-temperature shear, psi(MPa)	2903 (20)	4539 (31.3)
High-temperature shear, psi(MPa)		
140°F (60°C)	2903 (20)	4371 (30.1)
199°F (90°C)	1888 (13)	3883 (26.8)
Low-temperature shear, psi(MPa)	2175 (15)	3361 (23.2)
Humidity exposure, psi(MPa)	723 (5)	670 (4.6)
Salt spray exposure, psi(MPa)	2322 (16)	---
Normal-temperature floating roller peel, lbf/in. (N/m)	25.1 (4400)	34.1 (5978)
Low-temperature floating roller peel, lbf/in. (N/m)	15.0 (2625)	---
Dead load stress durability, hrs:		
40% of 140°F(60°C) failure stress	40	---
30% of 140°F(60°C) failure stress	540	---
20% of 140°F(60°C) failure stress	1500	---
Normal-temperature climbing drum peel, lbf·in./in. (N·m/m)	8 (36)	---
High-temperature climbing drum peel, lbf·in./in. (N·m/m)	4 (18)	---
Flatwise tensile strength, psi(MPa)	406 (2.8)	---

NOTE: (1) Adhesive Lot 904. Roll 42.

gel time at 275°F (135°C), and adhesive film weight tests have been completed and are reported in Tables 23 to 25. Further, data is also reported from a sample previously evaluated at UDRI. The tensile lap shear properties reported in Table 23 for the unknown lot number were obtained when the material was "fresh." The gel time and film weight results were measured on material from that same unknown lot number that had been in storage at UDRI for nearly 2 years at 0°F (-18°C). Note that while the tensile lap shear after humidity aging for the unknown lot number far exceeds the minimum value in the specification, Lot No. 965 barely meets the minimum and Lot No. 904 fails to meet the minimum. Neither Lot Nos. 904 nor 965 meet the requirement for film weight. There is no adhesive gel time requirement in the ASTM specification, but it is often used by the shelter manufacturer to check for lot-to-lot or roll-to-roll variations within a lot. The gel time for the unknown lot is about one-half of that for Lot 904 and slightly lower than that of Lot 965, indicating some variation. It is possible that the gel time of the unknown lot may be shorter due to its age.

3.10 Effect of Waterborne Chlorides on Surface Preparation for Adhesive Bonding

The standard practice for the preparation of aluminum skins used in honeycomb shelter panels is given by ASTM E864, "Surface Preparation of Aluminum Alloys to be Adhesively Bonded in Honeycomb Shelter Panels." In this specification the water used in the processing solutions and final rinsing is required to be either deionized or to have a maximum chloride content of 15 ppm. Not all regionally distributed potable water will meet this requirement. When large volumes of water are used, deionization can be very expensive. A test program has been conducted to help determine if the permissible chloride content level can be raised to 25 ppm. ASTM D3933, "Preparation of Aluminum Surfaces for Structural Adhesives Bonding (Phosphoric Acid Anodizing)," requires that the maximum chloride content be 25 ppm. ASTM D2651, "Preparation of Metal Surfaces for Adhesive Bonding," has no requirement for chloride content. Raising the maximum level from 15 to 25 ppm would bring E864 in line with other ASTM specifications.

Experiments were undertaken to determine what effect, if any, a chloride content of up to 45 ppm would have on adhesive properties. ASTM Committee, E06.53, on Relocatable Shelter Construction will have to evaluate the data generated in these experiments and decide whether or not to raise the chloride content requirement.

TABLE 23

TENSILE LAP SHEAR STRENGTHS FOR NEWPORT 101 ADHESIVE

Test Condition	Minimum(1) Requirement psi (MPa)	Lap Shear Strength, psi (MPa) Adhesive Lot No./Roll No.		
		904/42	965/109	Unknown(2)
72°F (22°C)	2903 (20)	4539 (31.3)	---	4420 (30.5)
140°F (60°C)	2903 (20)	4371 (30.1)	---	4120 (28.4)
200°F (93°C)	1888 (13)	3883 (26.8)	---	3500 (24.1)
-67°F(-54°C)	2175 (15)	3361 (23.2)	---	3110 (21.4)
Humidity(3)	723 (5)	448 (3.1)	757 (5.2)	1680 (11.6)
Salt Spray(4)	2322 (16)	---	---	3970 (27.4)

NOTES:

1. Minimum requirements per ASTM E865.
2. Typical values previously obtained at UDRI, Lot and Roll Nos. unknown.
3. 200°F (93°C) after 2 wks. @ 200°F (93°C) and 95-100% relative humidity.
4. 72°F (22°C) after 2 wks. @ 95°F (35°C) in 5% salt fog.

TABLE 24

GEL TIME AT 275°F (135°C) FOR NEWPORT 101 ADHESIVE

Lot No.	Roll No.	Gel Time
904	42	13 mins. 47 sec.
965	109	6 mins. 55 sec.
965	75	8 mins. 7 sec.
965	113	7 mins. 16 sec.
Unknown	Unknown	6 mins. 30 sec.

TABLE 25

FILM WEIGHT FOR NEWPORT 101 ADHESIVE

Lot No.	Roll No.	Film Weight lbs./ft.^{2} (Kg/m^2)	E865[1]
904	42	0.103 (0.50)	0.084 ± 0.004 (0.41 ± 0.02)
965	75	0.092 (0.45)	---
965	109	0.103 (0.50)	---
965	113	0.098 (0.48)	---
Unknown	Unknown	0.071 (0.35)	---

NOTE:

1. Maximum allowable film weight per ASTM E865.

Table 26 lists the materials, processes, and tests used to determine the effect of chloride content.

TABLE 26

GENERAL OUTLINE FOR PROJECT TO DETERMINE THE MAXIMUM ALLOWABLE CHLORIDE CONTENT IN PROCESSING SOLUTIONS AND RINSE WATER USED IN SURFACE PREPARATION OF ALUMINUM FOR SHELTER CONSTRUCTION

Materials

Aluminum, 6061-T6
- 0.063 inch (1.6 mm) for stress durability
- 0.125 inch (3.2 mm) for wedge crack
- 0.025 inch (0.6 mm) for climbing drum and floating roller peel

Adhesive, Ciba-Geigy R-382
Primer, BR-127

Processes

P2 and OFPL etch per ASTM E864
Water (solutions and rinse); deionized, 25 ppm and 45 ppm chloride

Test Methods

Wedge crack test per ASTM D3762, five specimens per process subjected to 120°F (49°C) and condensing humidity
Floating roller peel per ASTM D3167, five specimens per process at 72°F (22°C) and -65°F (-54°C)

All materials listed are those used in shelter construction. Both OFPL and P2 etches were used since both are qualified for shelter construction and it is unlikely that the effect of chloride content has ever been investigated using the P2 etch. The test methods selected were chosen after consulting shelter manufacturers and Air Force Materials Engineers.

The results obtained are shown in Tables 27 and 28. At this point, it is up to the ASTM Committee and the Air Force Project Engineer to make a decision on chloride content or to request additional study.

TABLE 27

EFFECT OF CHLORIDE CONTENT IN PROCESSING SOLUTIONS AND RINSE WATER UPON WEDGE CRACK GROWTH SPECIMENS(1)

Chloride Content	Length of Crack Growth, inches (2)							
	Initial	1 Hr.	4 Hrs.	8 Hrs.	24 Hrs.	7 Days	30 Days	Total(3)
Deionized	1.49	0.05	0.24	0.35	0.54	1.33	1.39	2.88
25 ppm	1.51	0.22	0.47	0.53	0.87	1.10	1.17	2.68
45 ppm	1.41	0.52	2.05	2.88	3.06	3.14	3.16	4.57

NOTES:

(1) Wedge crack growth at 120°F (49°C) and 95-100% R.H.
(2) Length of crack after initial, average of five specimens.
(3) Total crack length includes initial.

TABLE 28

EFFECT OF CHLORIDE CONTENT IN PROCESSING SOLUTIONS AND RINSE WATER UPON FLOATING ROLLER PEEL STRENGTHS

Chloride Content	Test Temperature °F (°C)	Floating Roller Peel Strengths, lbs/in (N/m)	
		OFPL	P2
Deionized	72 (22)	44.5 (77.9)	38.7 (67.8)
25 ppm	72 (22)	---	---
45 ppm	72 (22)	39.8 (69.7)	41.8 (73.2)
Deionized	-65 (-54)	22.9 (40.1)	24.9 (43.6)
25 ppm	-65 (-54)	---	---
45 ppm	-65 (-54)	17.6 (30.8)	19.5 (34.1)

4. SHELTER ARMOR

Air Force Tactical Shelters (AFTS) are very important components in the tactical command network. In a hostile environment the command and control functions of the shelter are critical. Therefore, there is substantial motivation to provide AFTS with protection from ballistic attack.

Although tactical shelters are not placed on the front lines, they may still be exposed to a variety of threats. The mobility requirements for shelters require, however, that armor be relatively lightweight. Excess weight can be avoided by adapting the armor to the hostility of the environment; thus applique armors are preferred in which individual applique panels be as light as possible.

The two principal ballistic threats that are of concern to shelters are small arms fire and fragments from artillery shells. The projectile associated with the first is a 0.30 cal AP (armor-piercing). Many fragment simulating projectiles (FSPs) have been used to simulate warhead fragments. The particular one specified for this study is a 60-grain right-circular cylinder. Both of these threats were considered in multi-hit scenarios.

Ballistic impact is not the only constraint on armor design. Service life requirements impose many other conditions, and armors that fail to meet non-ballistic requirements are not viable candidates for shelter applications. First, armors designed in a laboratory must be tolerant of the variations that inevitably occur in production. Armor designs that require materials available only from a single manufacturer must also be avoided in order to reduce the chances of cost growth or supply difficulties. There are also environmental demands on armors. High and low temperatures, thermal cycling, and moisture must be tolerated without significant loss of ballistic protection capabilities.

4.1 Armor I

Ceramic tiles bonded to metal or composite substrates have been used for lightweight armor since the late 1960's. On a previous program the University both reviewed this technology and carried out investigations of armor for AFTS protection (Ref. 1). After a review of those results, the Air Force decided to develop an armor design based on 85 percent theoretical density alumina tiles bonded to glass-reinforced plastic (GRP) backing panels.

In spite of past experience with these materials, several outstanding problems in design and fielding of ceramic armor systems remained.

(a) Ceramic tiles normally cannot withstand multiple hits. Multi-hit requirements, therefore, result in use of relatively small tiles in order to assure that it is unlikely for any tile to be hit twice. Consequently, impacts on edges (seams) and corners become much more likely. Smaller tile sizes and good performance at edges and corners generally require an increase in tile thickness.

(b) The GRP materials most often used in armor systems are based on starch oil sized fibers. The University showed that these materials are vulnerable to unacceptable degradation by moist environments. The environmental resistance of this type of armor must be increased for AFTS applications.

(c) Conventional ceramic/GRP systems are based on E-glass. An improved glass fiber, S-glass, has been shown to provide substantially better performance than E-glass and in many applications is equivalent to Kevlar reinforced plastic. Therefore, ceramic/GRP designs needed to be revised to take advantage of this new material.

(d) Previous work on AFTS ceramic armor was based entirely on one ceramic supplier, Coors Porcelain. In the past few years, however, the number of manufacturers of ballistic-grade ceramics proliferated. It was necessary to determine if there were other materials which are cost and performance competitive with Coors ceramics.

(e) It is very likely that in the next few years there will be a substantial upgrade in the lethality of small arms projectiles. This will be based on SLAP technology (saboted light armor piercing). It will probably be necessary to upgrade AFTS armor for these new threats in the near future. Unfortunately, the understanding of the penetration mechanics of ceramic armor is presently so primitive that the time required to develop SLAP armor may be unacceptable. Therefore, it was highly desirable that the design methodology for ceramic armor be improved.

The goal of the task undertaken here was to develop specific alumina/GRP multi-hit armor systems that meet all AFTS requirements. A large number of ballistic tests were conducted using armor piercing small arms projectiles. The ability of the

many target materials to resist penetration after multiple hits from these projectiles provided the basis for establishing the optimum armor design.

Since a separate and comprehensive technical report has been prepared that describes all the work carried out and results obtained on this project, only a summary overview of the effort will be described in the succeeding paragraphs. Armor parameters and variables that were investigated and optimized include:

(a) ceramic frontface material,
(b) reinforcing fiber in backup plate,
(c) fiber finish in backup plate,
(d) matrix resin in backup plate,
(e) adhesive between frontface material and backup panel,
(f) built-in delamination sites in backup plate,
(g) sandwich construction for backup plate,
(h) degree of cure in backup plate matrix resin,
(i) frontface thickness,
(j) backup plate thickness,
(k) tile shape on frontface,
(l) effect of environment,
(m) between-tile spacer material, and
(n) tile quality.

A new test procedure was devised and utilized to screen candidate frontface materials and investigate penetration mechanics. As a result of experiments with this test procedure, as well as information available from other sources, a four-stage penetration mechanism was hypothesized and acceptable ceramic frontface materials identified. The best backup plate composition was found to be an "S2" glass fabric with a fiber sizing that was semicompatible with a vinylester matrix resin.

After laboratory screening tests on smaller target sizes, full-scale applique armor panels (24 x 48 inches) (0.6 x 1.2 m) were fabricated and tested for multi-hit resistance against numerous single shots into adjacent tiles as well as against a burst of automatic fire hits. These full-scale tests were successful.

A technical report was prepared that described the materials and variables tested, the fabrication and test procedures, and the results in detail. As of this writing,

however, the report was still in review and had not yet been assigned an Air Force report number. The UDRI report number is UDR-TR-89-93.

4.2 Armor II

The objective of this task was to develop an armor system capable of defeating a 60-grain fragment simulating projectile (FSP). The target areal density of the armor system was 2 psf (9.8 Kg/m^2). Two general classes of armor were evaluated; fiber reinforced plastic (FRP) and glass-faced FRP. Available literature was reviewed. Penetration mechanisms for each class of armor were considered so that efficient screening procedures could be employed. Candidate armor materials were obtained from outside sources and also fabricated internally. All of the internally prepared armors employed FRP laminates prepared by a wet-layup procedure with a low viscosity, elevated temperature curing matrix resin. All ballistic tests were carried out in the UDRI Impact Physics Laboratory.

Ballistic testing of glass-faced armor demonstrated that it was less efficient than aluminum so this class of material was discontinued.

Four reinforcing fibers were evaluated in FRP armors; Kevlar, E-glass, S2-glass, and Spectra™*. Spectra is a recently developed polyethylene fiber having excellent impact properties.

The available literature on penetration mechanics of fibrous targets refers to systems with no matrix resin. While the results of these previous tests on dry fibrous systems provided some valuable insights, there were a number of issues and questions concerning penetration mechanics in resin matrix composites that remained unanswered. A series of experiments were consequently devised and carried out to elucidate these issues.

Screening tests on candidate armor systems were carried out on two target thicknesses, one below and one above the thickness expected to provide the desired level of protection. This permitted interpolation to accurately determine the areal density required to defeat the threat. The tests consisted of shooting the FSP projectile into a 1-foot (30.5-cm) square, rigidly clamped target at various velocities. Each panel was shot up to five times with either a complete or partial penetration being noted.

* Trademark of Allied Signal.

Ballistic testing was also carried out on target panels at reduced and elevated temperature and after elevated temperature, high humidity exposure to provide information on the environmental degradation of the armor systems. It was found that the environmental effects on the ballistic performance of all but one of the tested materials was negligible. This was a glass reinforced polyester resin system.

It was concluded, as a result of this investigation, that armor to defeat a 60-grain FSP at the threat velocity and meet all environmental requirements as well, could be fabricated from Spectra, Kevlar, or S2-glass reinforced plastics. Only a Spectra reinforced system, however, was able to accomplish this within the 2 psf (9.8 Kg/m^2) weight goal. The Spectra system in fact, met the requirement at only about half the 2 psf (9.8 Kg/m^2) areal density goal. A Kevlar reinforced system was able to defeat the threat at a weight only slightly over the goal (2.1 psf) (10.3 Kg/m^2). An S2-glass reinforced phenolic system was able to defeat the threat at an area density of 2.5 psf (12.2 Kg/m^2).

While the performance of the Kevlar reinforced system is not as good as that of the Spectra reinforced system, it is considerably less expensive than Spectra. Furthermore, the S2-glass reinforced phenolic system is only 20% heavier than the Kevlar system and is less expensive than the Kevlar. Thus, either Kevlar or S2-glass reinforced armors could be considered if cost were a significant factor.

A comprehensive technical report, WRDC-TR-89-4066 has been published that describes in detail the background, approach, procedures, materials, results, and conclusions of this investigation.

5. EMI/RFI SHIELDING AND DETECTION

Many technical shelter applications require EMI/RFI shielding to either protect internal equipment from interference or damage by external sources of electromagnetic energy or to prevent electromagnetic signals generated internally from being detected externally. While many shelters are constructed with built-in EMI/RFI shielding, many factors can degrade this shielding once the shelter leaves the factory floor, including handling and shipping damage, environmental degradation, and installation of equipment. No reliable and convenient means of assessing the current shielding levels in tactical shelters exists at present in either the field or depot environment.

Two tasks were undertaken in this program to address this issue. One involved the development of an automated, integrated EMI/RFI shielding monitoring system capable of scanning the entire shelter surface over the frequency range 100 kHz - 500 MHz. In addition, a hand-held 12 GHz sniffer was developed to be used in conjunction with the hardness assurance monitoring system (HAMS) to cover the high frequency regime. The second involved the evaluation of commercially available RF leak detectors to determine their utility and reliability in detecting shielding degradation and leaks.

5.1 Automated, Integrated EMI/RFI Monitoring

In the design and construction of an electromagnetically hardened shelter, a variety of protective elements such as metal shields, filters, and electrical surge arresters are used which are basically transparent to normal system operation. Daily activities usually provide no indication as to the condition of the electromagnetic (EM) protective elements and their ability to function when needed. Construction Engineering Research Laboratory (CERL) investigators (Ref. 2) have indicated that EM shielding performance of shelters can degrade under the most benign conditions.

The HAMS concept provides a means by which the status of the EM protective subsystem can be evaluated and presented to shelter users in near real time. Long-term field use of the HAMS will also provide extensive data on shielding performance as a function of time. Analysis of such data could lead to the development of scheduled, preventative maintenance procedures to restore shielding performance.

Two conceptual HAMS designs were developed and reported under a previous contract (Ref. 3).

Two followup activities to that work were undertaken on this program. Both were carried out under subcontract by Mission Research Corporation (MRC). The first consisted of the development, construction, and demonstration of a prototype HAMS system and was reported in AFWAL-TR-88-4064. The second consisted of an effort to identify commercially available, off-the-shelf components to replace specially developed components that were designed to maximize performance of the prototype system, and to further develop and select efficient sensor/driver pairs for use by the HAMS in fault detection. These two efforts are discussed separately in the succeeding sections.

5.1.1 Prototype Development of HAMS

This effort consisted of the development of a technically effective prototype hardware system that emphasized the use of components with a low life-cycle cost. Expensive, fragile laboratory equipment was avoided where possible. Where a choice of alternative components was available, the simpler, more rugged, and less expensive items were selected.

The major portion of this effort was the design and manufacture of a computer controlled matched receiver and transmitter. The design incorporated the superheterodyne technique of a typical radio receiver. This particular technique provides excellent sensitivity while allowing for a relatively simple detection scheme. The system is capable of measuring EM shielding integrity using discrete frequencies over the band of 100 kHz to 500 MHz.

The HAMS is comprised of three basic elements. The first is the transmitter/receiver, the second is the computer/microprocessor for control and data recording, and the third is the sensor/driver pairs. The result of this effort was that a complete automated prototype HAMS covering the band of 100 kHz to 500 MHz was developed. The design implemented was based on highly reliable old technology. The components used were easily procured in a reasonable time frame and found in most cases to be adequate for use without modification. The system worked well in the laboratory with continuous operation in excess of 72 hours. The physical design of the prototype system was not ruggedized and therefore is not intended for field use.

A hand-held, 12 GHz "sniffer" was developed for use in locating leaks detected by the HAMS. The sniffer is battery powered and capable of determining the magnitude of the leak within a 2 dB tolerance.

The HAMS prototype system was installed in a laboratory screen room and EMI/RFI leak measurements were made on the baseline and intentionally degraded screen room. It was also installed on an S250C/G tactical shelter. Data from HAMS measurements made on both the screen room and the tactical shelter are presented and discussed. A detailed description of the design, construction, and operation of the HAMS is given in Air Force technical report number AFWAL-TR-88-4064.

5.1.2 Further Development of HAMS

The prototype HAMS described in the preceding section incorporated a number of specially developed components in the receiver/transmitter sections and narrow bandwidth driver/receiver antennas to demonstrate system feasibility. A first step in making the HAMS design more usable is the replacement of these specialty components with commercial equivalents. This follow-on effort had two objectives: (1) the identification of commercial replacement components for the HAMS, and (2) further development of efficient sensor/driver pairs for use by the HAMS.

The component survey consisted exclusively of telephone contact with numerous manufacturers. A comprehensive tabulation of commercial alternatives to the MRC manufactured components used in the HAMS was prepared.

Six sensor/driver pairs were characterized and used in this effort. Sensor/driver pair characterization employed two network analyzers covering the frequency range of 100 kHz to 500 MHz. Three sensor configurations (series loop, bare coaxial cable core, and slotted coax) emerged from these tests as useful configurations. These three exhibited good wideband response characteristics, allowing them to be used as radiators and detectors for a wide variety of fault types. The three sensor configurations that were not effective were folded inductors, leaky coaxial cable, and parallel loop. Each of the six sensor/drive configurations are discussed in greater detail, and illustrated in WL-TR-91-4093.

Lastly, since the HAMS operates only up to 500 MHz, a hand-held sniffer unit that operates at 12 GHz was developed to meet the high frequency

requirement. A detailed description of the work undertaken to further develop the HAMS, test results obtained, and conclusions arrived at is presented in Air Force technical report WRDC-TR-91-TBD.

5.2 Evaluation of Portable RF Leak Detectors

The HAMS system described in Section 5.1 would most likely be initially employed during depot-level maintenance activities. While it may eventually become a fully commercialized system installed in shelters for in-field shielding monitoring, this is some years in the future. Field operators of shelterized systems have an immediate need to determine real time shielding performance of their shelters. At the current time there is no way to determine if the EMI/RFI shielding level has been compromised by damage, corrosion, or routine wear and tear. Portable radio frequency (RF) leak detectors, commonly known as "sniffers," are available in the commercial marketplace that provide a means of assessing shielding levels.

An evaluation of four commercial RF leak detectors was carried out. These are listed in Table 29. The evaluation of these sniffers entailed comparing sniffer

TABLE 29
COMMERCIAL RF LEAK DETECTORS

Designation	Source	Operating Frequency
4F-130	Euroshield	10 kHz, 150 kHz, 1 MHz, 10 MHz
TS-450	ASM	450 MHz
SELDS 3500	Eaton	106 KHz
SIMS II	Ray Proof	462.6 MHz

test data to date collected in standard ML-STD-285 tests on an S250 C/G tactical shelter and to evaluate reliability, ease of operation, battery life, and sensitivity.

The S250 shelter was characterized in accordance with MIL-STD-285 over the frequency range 10 kHz to 12 GHz. The intermediate frequencies selected coincided with the operating frequencies of the sniffers as well as those recommended in the standard. Several intentional faults were fabricated for use in evaluating the sniffers since no well-defined or controlled faults existed on the shelter. This was done by

replacement of a 24-inch x 36-inch (0.6 m x 0.9 m) "kick" panel on the door with a steel panel having various fault types.

The sniffer data compared favorably with the baseline MIL-STD-285 tests with one notable exception for the ASM unit. This unit displayed an unusual dependence on shelter grounding. When the shelter was grounded the ASM test results were virtually identical to the SIMS II data. All of the sniffers performed as expected for their frequency of operation. None outperformed the others in the ability to determine shielding effectiveness of the shelter with the exception of the Eaton SELDS. This unit does not determine shielding levels, only the presence of faults. The best unit, for overall reliability and ease of operation, however, was the Euroshield unit.

A detailed description of the work carried out to evaluate these four commercial sniffer units and the test results obtained, is presented in Air Force technical report WL-TR-91-4093.

6. LONG-TERM TROPIC ENVIRONMENTAL EXPOSURE OF ARMY STANDARD FAMILY (ASF) RIGID WALL HONEYCOMB SANDWICH PANELS

This project was initiated under Air Force Contract F33615-84-C-5079 and continued to completion during this contract. The project is complete and a final report was written. The following is an overview of this effort, which took more than 5 years to complete.

6.1 Introduction

The Army Standard Family (ASF) of Tactical Rigid Wall shelters are general purpose in nature and are intended for providing a clean/dry live-in/and work-in environment for field hospital surgery, pharmacy, laboratory, maintenance of equipment, field bakery, field modular print systems, etc. Many of these shelters are constructed to conform with requirements set by the International Organization for Standardization for shipping containers and are designed as ISO shelters. They are deployed world wide and consequently are subjected to a wide range of environmental conditions. Experience has demonstrated that the hot-humid environment of the tropics may be the most demanding on adhesively bonded shelter panels.

Natick Labs in cooperation with the Air Force Materials Laboratory at Wright-Patterson Air Force Base, with support from the University of Dayton Research Institute (UDRI) and Hexcel, set out to establish a technical data base for ISO shelter panel structural integrity with long-term exposure to the tropical environment. Thirty-two (32) panels were fabricated and shipped to the U.S. Army Tropic Test Center (USATTC) in the Republic of Panama for exposure and evaluation.

6.2 Panel Description

Twenty-four of the panels had 2-inch (5.08 cm) thick resin impregnated Kraft paper honeycomb core, 3.8 lbs/ft^3 (61 Kg/m^3), 3/8-inch (0.95 cm) cell size per ASTM E1091. Open cell friable 3/4-inch (1.9 cm) thick polyurethane foam insulation was pressed within the honeycomb cells and were identified as panel numbers 1 to 24. Eight panels had 2-inch (5.08 cm) thick 4.4 lbs/ft^3 (70.6 Kg/m^3), 1/4-inch (0.64 cm) cell resin impregnated Nomex paper honeycomb core and the same 3/4-inch (1.9 cm) polyurethane foam insulation pressed into the cells and were identified as panel numbers 25 to 32. All of the panels were 4 ft. wide and 8 ft. long (1.2 m x 2.4 m) having the

honeycomb core ribbon in the 8-ft. (2.4 m) length direction. The outside or top skin was 0.050 inch (1.27 mm) thick 5052-H34 aluminum painted forest green and the inside or bottom skin is 0.040 inch (1 mm) thick 5052-H34 aluminum painted white. Panels were made in accordance with Natick drawing 5-4-2844 for ASF hinged roof panel assembly except without hinges and all four edges were closed.

6.3 Panel Construction

ASF deployable roof panels were constructed to assess the long-term effects on individual panel structural integrity as a function of hardware attachments (latches), inserts, simulated damage, repair patching, cut-outs, and the use of polysulfide sealant. In addition, humidity indicators were installed to assess moisture intrusion into each panel during tropical exposure. Four types of panels were constructed and are identified in Table 30.

TABLE 30

LONG TERM TROPICAL EXPOSURE PANEL IDENTIFICATION

(1) Standard Panels, closed edges, foam insulation, and polysulfide sealant
Kraft Core - Nos. 1, 2, 3, 4, 5, 6, 7
Nomex Core - Nos. 25, 26

(2) Hardware Panels, closed edges, partial foam insulation, latches, inserts, cut-outs, repair patch, and polysulfide sealant
Kraft Core - Nos. 8, 9, 10, 11, 12, 13, 14
Nomex Core - Nos. 27, 28

(3) Simulated Damage Panels, closed edges, foam insulation, and hardware or inserts, and 2-inch (5.08 cm) diameter holes in skin(s) only to simulate damage, and polysulfide sealant
Kraft Core - Nos. 15, 16, 17, 18, 19, 20
Nomex Core - Nos. 29, 30

(4) No Sealant Panels, closed edges, foam insulation, no hardware or inserts, and with no polysulfide sealant
Kraft Core - Nos. 21, 22, 23, 24
Nomex Core - Nos. 31, 32

Details of the location of latches, inserts, cut-outs, and repair patch are shown in Figures 4 and 5. The location of three 2-inch (5.08-cm) diameter holes in

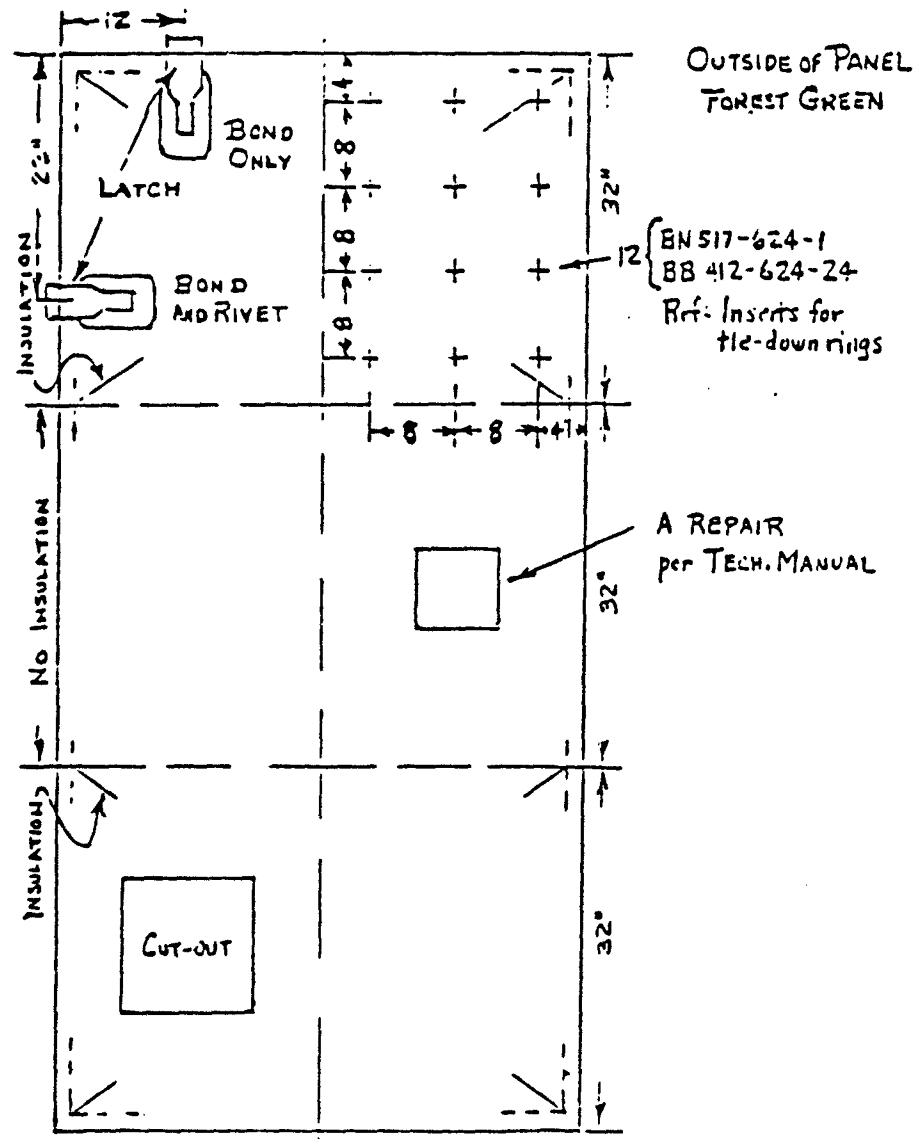


Figure 4. Outside of Hardware Panel Showing Location of Latches, Inserts, Repair Patch, and Cut-out.

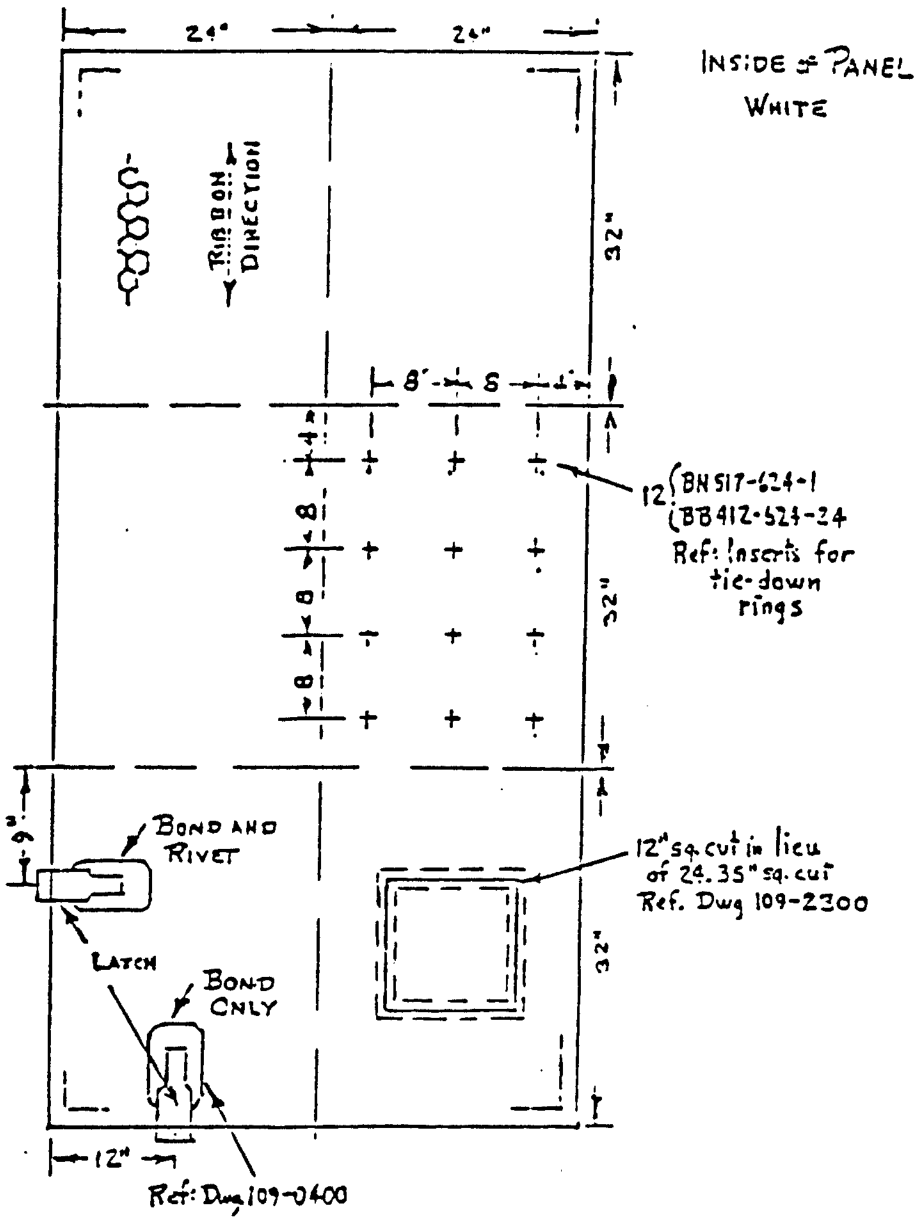


Figure 5. Inside of Hardware Panel Showing Location of Latches, Inserts, and Cut-out.

skin(s) to simulate damage are shown in Figure 6. The humidity indicators installed during construction are sealed from the outside environment and are only visible on the inside skin. The indicators are designed to change color (blue to pink) when relative humidity within the panel reaches 70%, 80%, or 95%. Color change is reversible if relative humidity drops below the indicated level. Location of the humidity indicators is shown in Figure 7.

The materials, equipment, and procedures used in the manufacture of the panels for environmental exposure were the same as that required in the production of tactical shelters. After manufacture the panels were packed in wooden crates and shipped to the USATTC in Panama.

6.4 Test Plan

The plan was to deliver the 32 fabricated panels to the USATTC in Panama in advance of the first visit by representatives of the Natick, UDRI, and Hexcel. Upon arrival at TTC the representatives were to observe, instruct, and generally oversee the handling of the panels, and the preparation, cutting, and testing of the specimens. In reality this was not the case. The actual work had to be performed by the representatives from Natick, UDRI, and Hexcel with assistance from USATTC personnel. This did not pose a problem because the representatives had many years of testing experience. Also, UDRI and Hexcel supplied the test fixture required to perform the mechanical property tests on the USATTC Instron Universal test machine, Model No. 1125.

Prior to testing, each panel was visually inspected, coin tapped on both sides, and weighed. Also, all humidity indicators were inspected to insure all were blue. Four panels were cut into test specimens for initial base-line data. Twenty-five were exposed to the tropical environment, and three were stored at standard conditions (73°F (23°C), 50% R.H.) in the laboratory at TTC. Table 31 lists the panel numbers and withdraw sequence.

Upon removal from the exposure rack, each panel was visually inspected for corrosion, bulges, fungus and algae growth, peeling of paint, sealant deterioration, etc. Each panel was weighed to assess moisture pick-up, and coin tapped over the entire surface of both sides. Test specimen location and size were next drawn on each panel using a different master drawing for each of the four type panels. Next, each panel was cut into specimens using a deep throat band saw. Table 32 lists the type mechanical

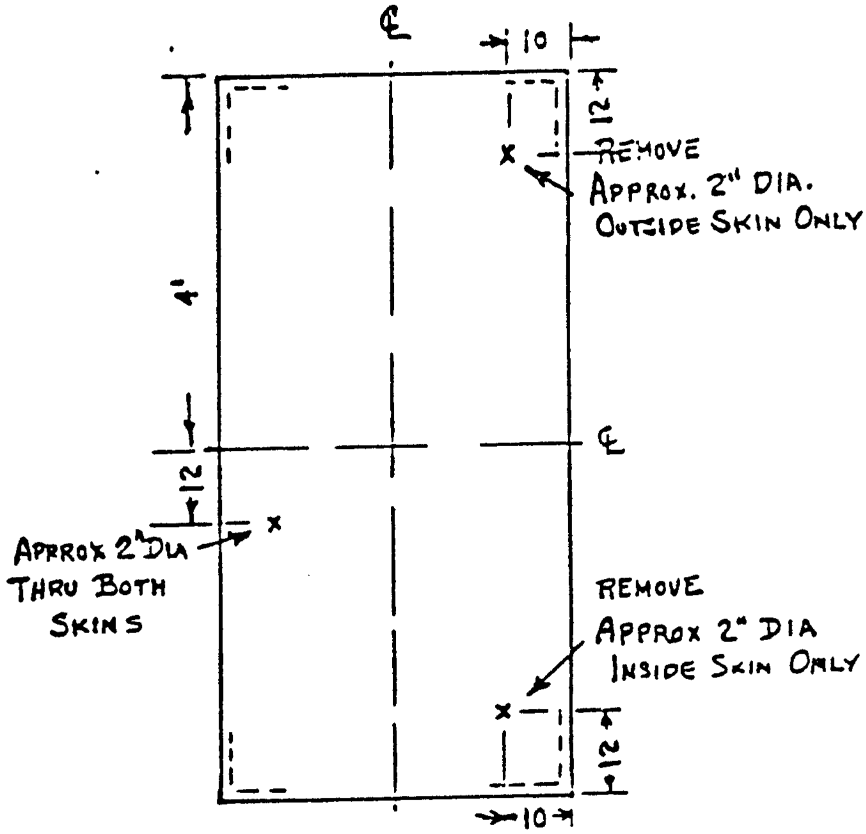
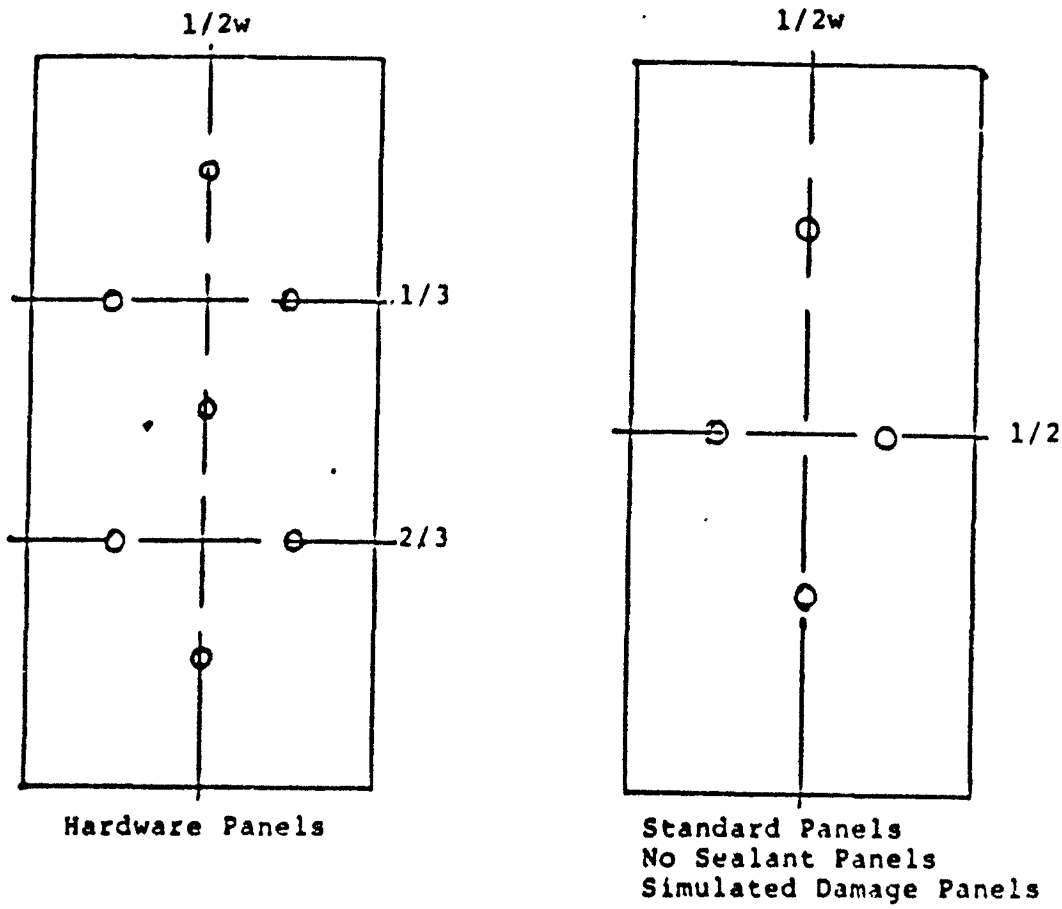


Figure 6. Location of 2 Inch (5.08 cm) Diameter Holes for Simulated Damage.

LOCATION OF GAUGES

INSIDE SURFACE



o HUMIDITY INDICATORS, NO. 2156
HUMIDIAL CORP., COLTON, CA

Figure 7. Location of Humidity Indicators.

TABLE 31

LONG TERM TROPICAL EXPOSURE PANEL WITHDRAW DATES

Exposure Time	Date	Panel Numbers
Control	Oct. 1983	2, 8, 27, 29
6 Month	April 1984	2, 9, 15
1 Year	Oct. 1984	3, 10, 16, 21, 31
2 Year	Oct. 1985	4, 11, 17, 22, 25
3 Year	Oct. 1986	5, 12, 18, 23
5 Year	Oct. 1988	6, 7, 13, 14, 19, 20, 24, 26, 28, 30, 32

NOTE: Panels 7, 14 and 20 are stored at standard conditions.

TABLE 32

MECHANICAL PROPERTY TESTS, SPECIFICATIONS, AND SPECIMEN SIZES

Type Test	Test Specification	Specimen Size
Climbing Drum Peel	ASTM D1781	3 inch x 12 inch (7.6 x 30.5 cm)
Flatwise Tension	MIL-STD-401B	3 inch x 3 inch (7.6 x 7.6 cm)
Flatwise Compression	MIL-STD-401B	4 inch x 4 inch (10.2 x 10.2 cm)
Sandwich Flexure	MIL-STD-401B	3 inch x 15 inch (7.6 x 38.1 cm)
Insert Pullout and Torque	MIL-STD-907	N.A.
Sealant Durometer	ASTM D2240	N.A.

property measured, applicable test specification and specimen size. Table 33 lists those same mechanical property tests, appropriate specification, and minimum requirement for use in tactical shelters. Figures 8 through 11 illustrate the master panel diagrams used in locating each specimen type in each panel configuration.

6.5 Discussion of Results

The goal of the long term tropic environmental exposure of rigid wall honeycomb sandwich panels was to determine the effect of that exposure on physical and mechanical properties over a 5-year period. All visual, physical, and mechanical tests were completed beginning October 1983 and ending November 1988. Results include those for control, 6-month control, 6-month, 1-year, 2-year, 3-year, and 5-year tropical exposure. The 6-month control resulted from difficulties with the Instron test machine while testing compression specimens during the initial vist to Panama. Consequently, some specimens originally intended for control were stored in the laboratory for 6 months and then tested with the 6-month withdrawal specimens. Upon withdrawal from tropical exposure each panel was subjected to a variety of visual, physical, and mechanical tests.

6.6 Visual Inspection, Tap Testing, and Panel Weights

All panels were visually inspected, coin tap tested, and weighed before being placed in racks at the Chiva-Chiva test site, tested for control data, or stored in the controlled environment in the Materials Lab at the Tropic Test Center.

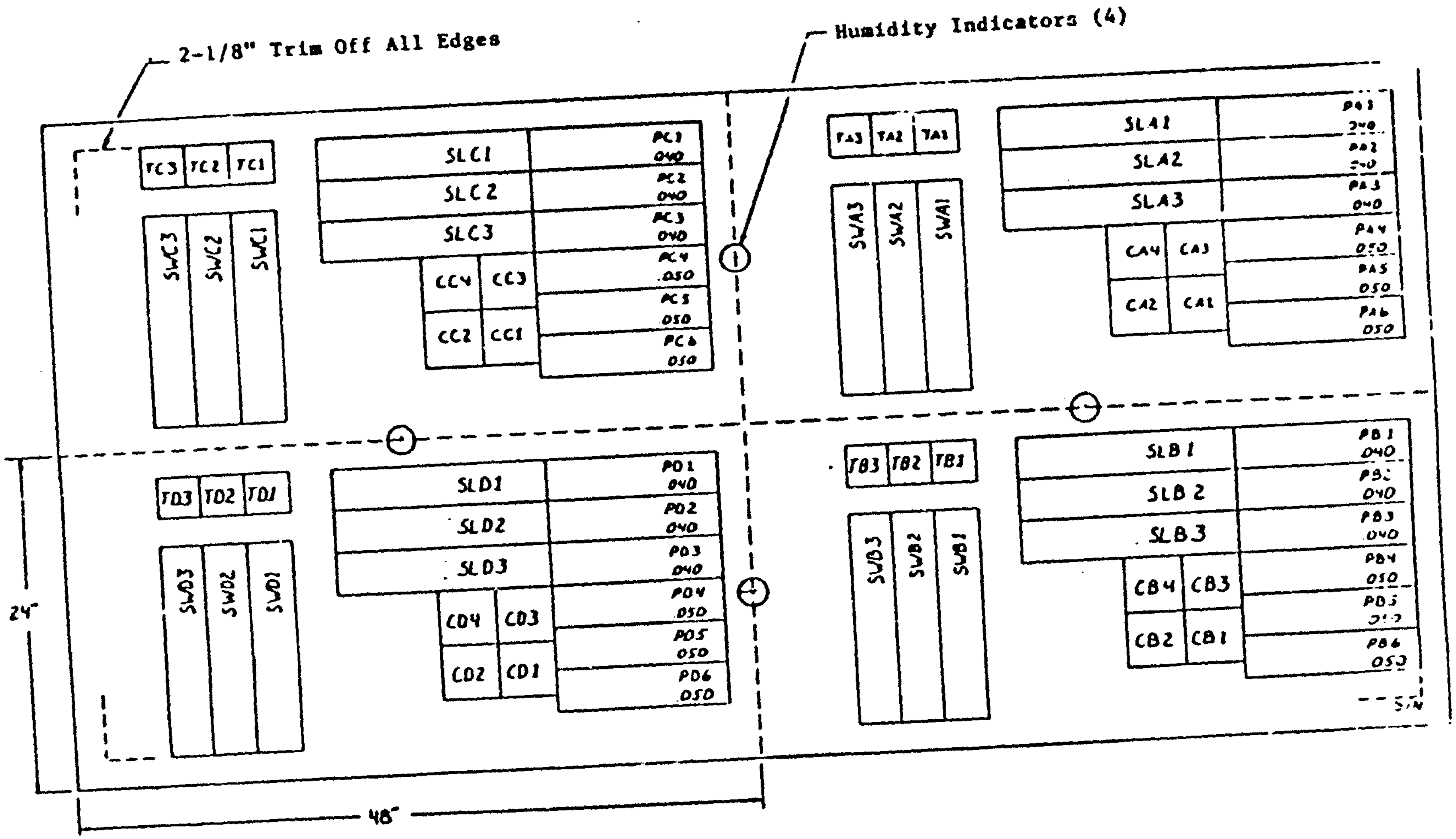
Initially the panels looked in good shape except for the "dings" in the panels caused by improper packing for shipment to Panama. These "dings" were from the humidity indicators from the bottom side of one panel striking the top side of another. These were not expected to cause any problems because specimens were not to be machined from the panels in the immediate area. Close attention was given these areas and as expected no adverse effects, including no delaminations, resulted from these "dings" over the 5 years of exposure.

After 6 months of tropical exposure, some fungus growth was noted on the bottom side of each panel. After 1 year the fungus had totally covered the bottom and then thickened after 2 years and stained the white paint after 3 years. Also, after 2 years exposure, algae began to appear on the lower edge of the top side of some panels and this spread upward after 3 years. No attempt was made to identify the particular type

TABLE 33

MINIMUM REQUIREMENTS FOR MECHANICAL PROPERTIES FOR USE IN HONEYCOMB PANELS FOR TACTICAL SHELTERS

Type Test	Specification	Minimum Requirement
Climbing Drum Peel	ASTM E874	6.9 in.-lb/in. (3.1 Kg-m/m)
Flatwise Tension	MIL-H-43964 and ASTM E1091	306 psi (2.1 MPa)
Flatwise Compression	MIL-H-43964 and ASTM E1091	404 psi (2.8 MPa)
Sandwich Flexure	MIL-H-43964 and ASTM E1091	108 psi (0.74 MPa), "L" direction
Sandwich Flexure	MIL-H-43964 and ASTM E1091	113 psi (0.78 MPa), "W" direction
Insert Pullout	MIL-STD-907B	1600 lbs. (727 Kg), 80% 2000 lbs. (909 Kg), proof
Insert Torque	MIL-STD-907B	384 in.-lbs (443 Kg-cm), 80% 480 in.-lbs (554 Kg-cm), proof
Sealant Durometer	---	---

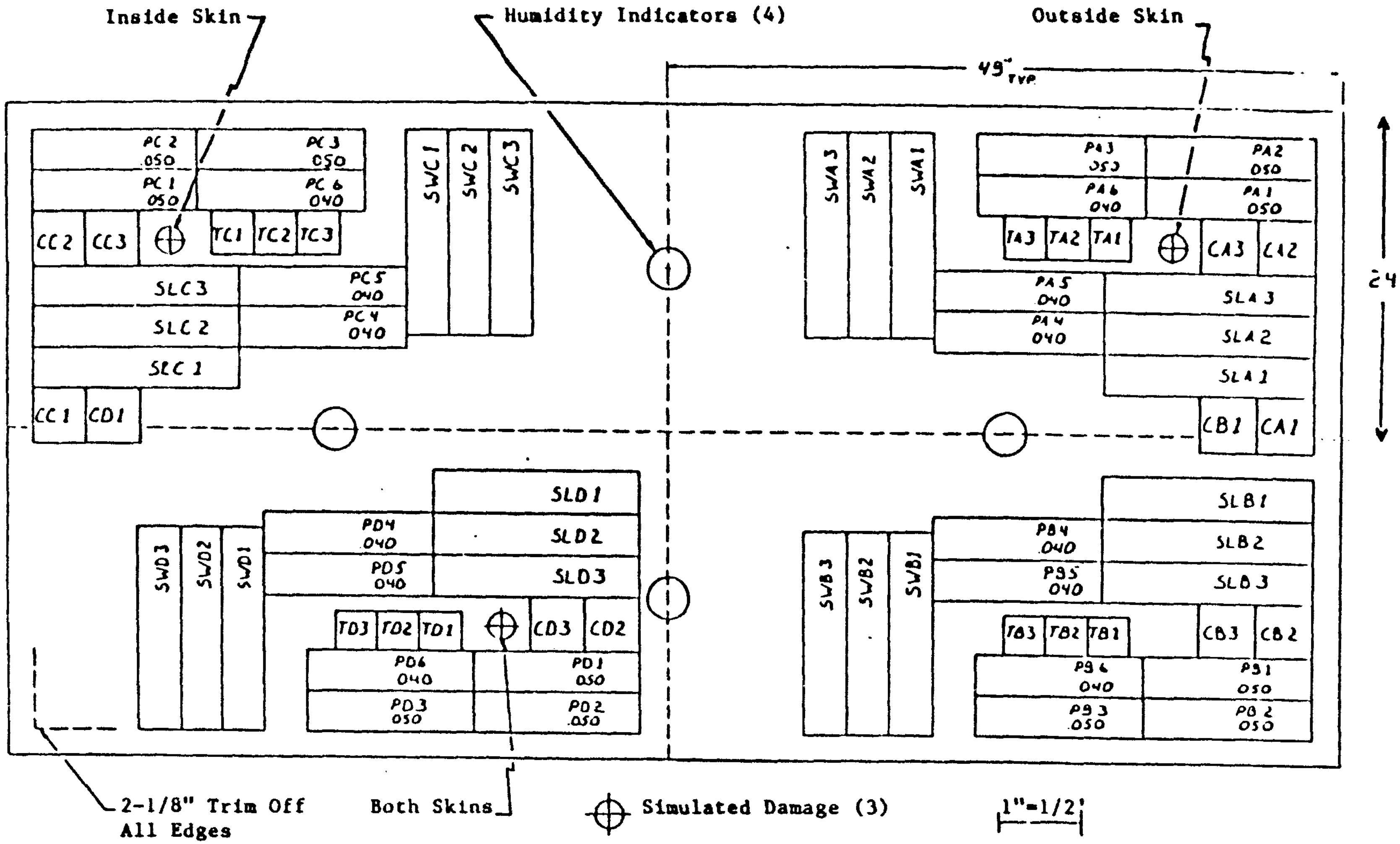


1"=1/2

Standard Configuration Panels - Kraft Core Nos. 1 to 7 Nomex Core Nos. 25, 26

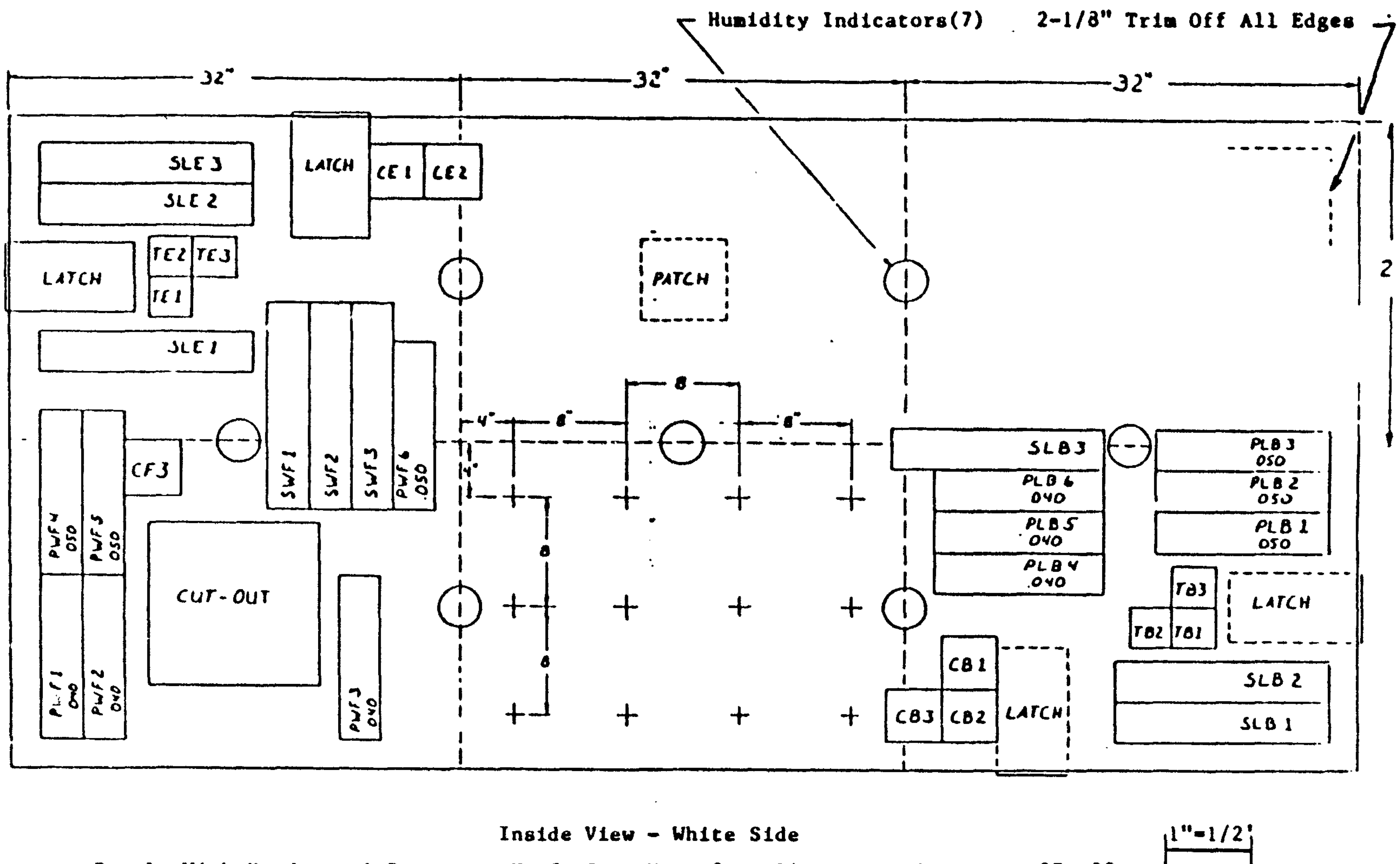
No Polysulfide Sealant - Kraft Core Nos. 21 to 24 Nomex Core Nos. 31, 32

Figure 8. Specimen Location for Standard Configuration and No Polysulfide Sealant Panels.



Simulated Damage Panels - Kraft Core Nos. 15 to 20 Nomex Core Nos. 29, 30

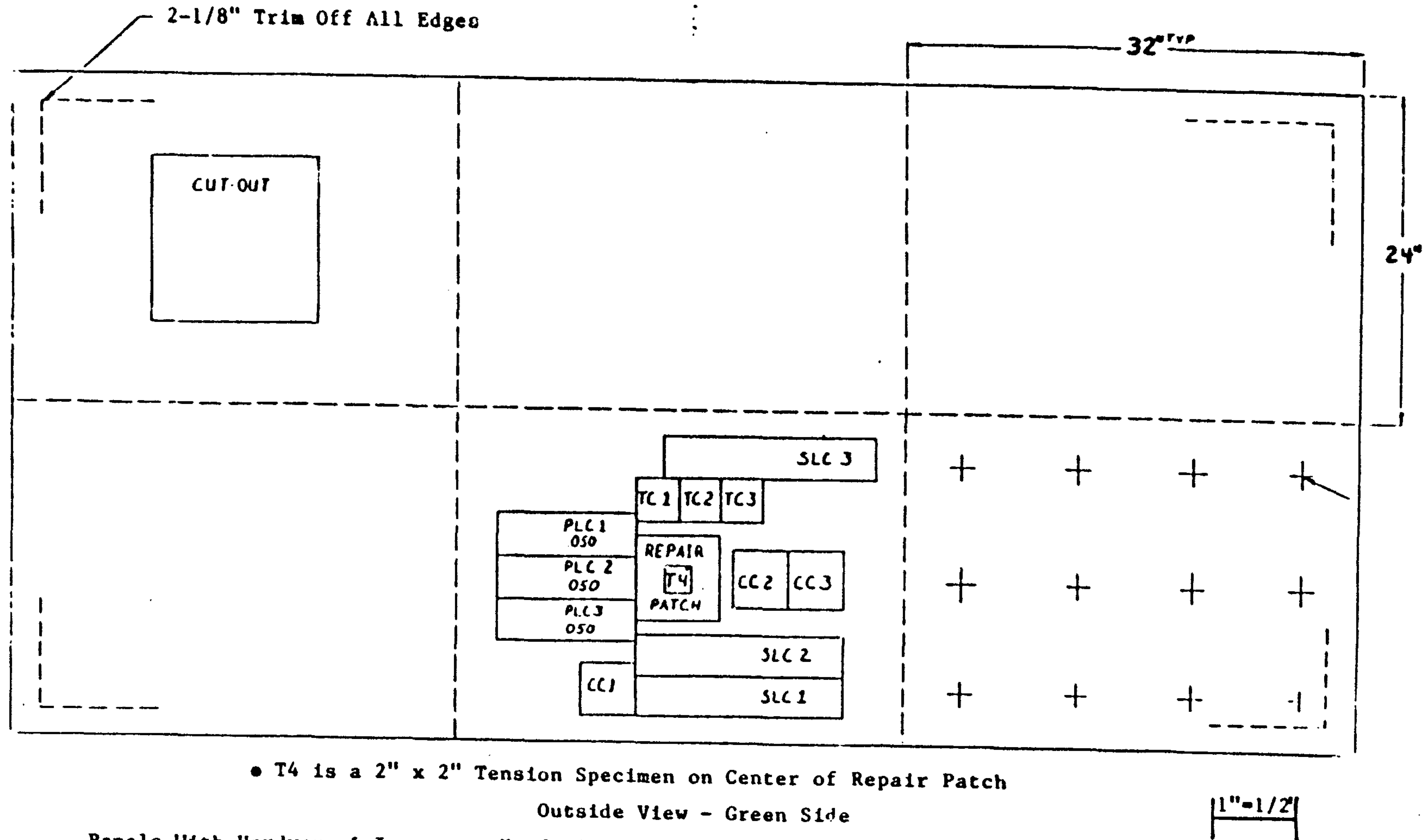
Figure 9. Specimen Location for Simulated Damage Panels.



Inside View - White Side

Panels With Hardware & Inserts - Kraft Core Nos. 8 to 14 Nomex Core Nos. 27, 28

Figure 10. Specimen Location for Inside (White) of Hardware Panels.



• T4 is a 2" x 2" Tension Specimen on Center of Repair Patch

Outside View - Green Side

Panels With Hardware & Inserts - Kraft Core Nos. 8 to 14 Nomex Core Nos. 27, 28

P-Peels = 3"x12" C-Compression = 4"x4" T-Tension = 3"x3" S-Shear = 3"x15"

Figure 11. Specimen Location for Outside (Green) of Hardware Panels.

of fungus or algae. Speculation that fungus would grow on the bottom and algae on the top was based on the prior experience of personnel at the Tropic Test Center. Upon withdrawal both surfaces were washed with warm water and both the fungus and algae were easily removed except for the staining on the bottom side. The white side of each panel would return nearly to its original luster but the green side became faded, in particular after 3 and 5 years. The only paint peeling or corrosion noted was that on the latches.

The embedded humidity indicators in each panel are designed to change color, from blue to pink, if the humidity reaches 70, 80, or 90% in those identified areas. After 5 years, none changed color. Since the process is reversible, TTC personnel were requested to periodically inspect them. They also have reported no color change.

All panels were thoroughly coin tap tested on both sides during the initial visit to Panama. Upon each withdrawal up to 3 years, all panels in the racks at Chiva-Chiva were then also coin tap tested. Between 3- and 5-year withdrawal, the panels were moved from Chiva-Chiva to a more secure area in Fort Clayton. During the fifth year withdrawal the panels were then coin tap tested at the new exposure site. During the 3- and 5-year withdrawal the panels being stored in controlled conditions were also tap tested. Special attention was given the areas around the "dings" and the holes which simulate damage. No delaminations were detected by coin tap testing.

All panels were weighed initially and then reweighed upon withdrawal. The weights of Kraft paper core panels are shown in Table 34 and the Nomex paper core in Table 35. Each panel weighs about 100 lbs (45.5 Kg). Three panels had gained what was considered a significant amount of weight. When cutting these panels into specimens for mechanical property tests, water ran from the closeout perimeter frame channelling. It is suspected that little moisture actually penetrated into the interior core of these panels. Two of these panels, Nos. 21 and 23, were panels with no polysulfide sealant, and the third, No. 5, was a standard configuration. It is suspected that as the sun shines on the panel, the air in the closeouts expands. If a rain storm suddenly occurs, which it often does, the panel rapidly cools, the air contracts and a vacuum is created in the closeout which sucks water in through the corners if they are not properly sealed.

TABLE 34

KRAFT PAPER CORE PANEL WEIGHTS

Panel	Weight: Initial/Final lbs (Kg)	Weight: Change (%)	Exposure
#1 Kraft, Standard	97.25/--- (44.2/---)	---	Control
#8 Kraft, Hardware	111.25/--- (50.7/---)	---	Control
#2 Kraft, Standard	95.15/95.09 (43.3/43.2)	-0.06	6 Mo. Tropical
#9 Kraft, Hardware	114.63/114.81 (52.1/52.2)	0.18	6 Mo. Tropical
#15 Kraft, Damaged	94.75/94.81 (43.1/43.1)	0.06	6 Mo. Tropical
#3 Kraft, Standard	97.00/96.91 (44.1/44.1)	-0.09	1 Yr. Tropical
#10 Kraft, Hardware	106.75/106.80 (48.5/48.5)	0.05	1 Yr. Tropical
#16 Kraft, Damaged	95.13/95.31 (43.2/43.3)	0.18	1 Yr. Tropical
#21 Kraft, No Sealant	96.15/98.40 (43.7/44.7)	2.25(1)	1 Yr. Tropical
#4 Kraft, Standard	97.15/97.30 (44.2/44.2)	0.15	2 Yr. Tropical
#11 Kraft, Hardware	114.00/114.20 (51.8/51.9)	0.20	2 Yr. Tropical
#17 Kraft, Damaged	97.31/97.70 (44.2/44.4)	0.57	2 Yr. Tropical
#22 Kraft, No Sealant	96.00/96.50 (43.6/43.9)	0.50	2 Yr. Tropical

NOTE: 1. Water in close-out channel.

TABLE 34 (Continued)

KRAFT PAPER CORE PANEL WEIGHTS

Panel	Weight: Initial/Final lbs (Kg)	Weight: Change (%)	Exposure
#5 Kraft, Standard	94.56/96.40 (43.0/43.8)	1.84 (1)	3 Yr. Tropical
#12 Kraft, Hardware	108.75/108.75 (49.4/49.4)	0.00	3 Yr. Tropical
#18 Kraft, Damaged	94.7/95.95 (44.4/43.6)	1.25	3 Yr. Tropical
#23 Kraft, No Sealant	95.65/96.90 (43.5/44.0)	1.25 (1)	3 Yr. Tropical
#6 Kraft, Standard	96.75/96.75 (44.0/44.0)	0.00	5 Yr. Tropical
#7 Kraft, Standard	95.69/95.80 (43.5/43.5)	0.11	5 Yr. Control
#13 Kraft, Hardware	109.50/109.60 (49.8/498)	0.10	5 Yr. Tropical
#14 Kraft, Hardware	108.00/108.10 (49.1/49.1)	0.10	5 Yr. Control
#19 Kraft, Damaged	96.25/97.15 (43.8/44.2)	0.90	5 Yr. Tropical
#20 Kraft, Damaged	96.00/96.20 (43.6/43.7)	0.20	5 Yr. Control
#24 Kraft, No Sealant	96.13/96.20 (43.7/43.7)	0.07	5 Yr. Tropical

NOTE: 1. Water in close-out channel.

TABLE 35

NOMEX PAPER CORE PANEL WEIGHTS

Panel	Weight Initial/Final lbs (Kg)	Weight Change (%)	Exposure
#27 Nomex, Hardware	111.31/--- (50.6/---)	---	Control
#29 Nomex, Damaged	99.52/--- (45.2/---)	---	Control
#31 Nomex, No Sealant	101.76/102.56 (46.3/46.6)	0.80	1 Yr. Tropical
#25 Nomex, Standard	101.52/102.05 (46.1/46.4)	0.53	2 Yr. Tropical
#26 Nomex, Standard	101.04/101.20 (45.9/46.0)	0.16	5 Yr. Tropical
#28 Nomex, Hardware	111.16/111.25 (50.5/50.6)	0.09	5 Yr. Tropical
#30 Nomex, Damaged	99.84/100.50 (45.4/45.7)	0.64	5 Yr. Tropical
#32 Nomex, No Sealant	100.98/102.95 (45.9/46.8)	1.97 (1)	5 Yr. Tropical

NOTE: 1. Moisture was visible in lower edge of panel.

6.7 Flatwise Compression

Flatwise compression test specimens were machined from each panel configuration. Except for hardware panels, each configuration is divided into quarters and at least three specimens are located in each of those quarters. Specimen location for all panels are shown in Figures 8 to 11. The compression tests were conducted at a crosshead speed of 0.01 inch (0.25 mm) per minute. Minimum values of compressive strength for honeycomb sandwich panels used in shelter construction have been established and are presented in ASTM E1091. The minimum compression strength for Type IV honeycomb core is 404 psi (2.8 MPa). All of the compression specimens have met these minimum guidelines. The worst results came from those specimens in the laboratory controlled environment for 6 months. The compression strength measured for Kraft paper core specimens stored in the laboratory environment was reduced 20% from those specimens having no exposure or 6-month tropical exposure. The measured compression strengths obtained for Nomex core were unchanged after the 6-month controlled environment. After 2 years of tropical exposure, the compression strengths for panels with Kraft paper core may be declining slightly, but still met minimum specification values. A summary of the Kraft paper core compression strengths is shown in Table 36 and the Nomex paper core strengths in Table 37.

6.7.1 Compression Near Simulated Damage

The flatwise compression test may be one which is very sensitive to the effect of environmental exposure on sandwich panel mechanical properties. For this reason compression specimens are located very close to the holes simulating damage. The simulated damage panels are divided into quarters, "A" having a hole in the top skin, "B" having no hole, "C" having a hole in the bottom skin, and "D" having a hole in both skins. As expected, in most cases the average compression strength from the quarter with no holes is the highest and the quarter with the hole in the top skin only is the lowest. During several visits to the exposure site, water could be seen standing in the cells with a hole in the top skin only. During the panel withdraw up to the 2-year exposure, a piece of the panel containing the holes was cut, sealed in a plastic bag, and returned for use as visual aids while presenting the results at various meetings. This was of some value because water would evaporate from the core and condense on the plastic bag. As one would expect, the sealed bag with the specimen having a hole in the top skin only would have the most water. During the 3-year withdraw it was decided that

TABLE 36

KRAFT PAPER CORE COMPRESSION STRENGTHS

Panel	Exposure	Avg. Strength psi (MPa)
#1 Kraft, Standard	None	530 (3.65)
#1 Kraft, Standard	6 Mo. Controlled	433 (2.98)
#2 Kraft, Standard	6 Mo. Tropical	517 (3.56)
#3 Kraft, Standard	1 Yr. Tropical	609 (4.20)
#4 Kraft, Standard	2 Yr. Tropical	523 (3.60)
#5 Kraft, Standard	3 Yr. Tropical	513 (3.53)
#6 Kraft, Standard	5 Yr. Tropical	525 (3.62)
#7 Kraft, Standard	5 Yr. Controlled	461 (3.18)
#8 Kraft, Hardware	None	572 (3.94)
#8 Kraft, Hardware	6 Mo. Controlled	433 (2.98)
#9 Kraft, Hardware	6 Mo. Tropical	553 (3.81)
#10 Kraft, Hardware	1 Yr. Tropical	560 (3.86)
#11 Kraft, Hardware	2 Yr. Tropical	622 (4.29)
#12 Kraft, Hardware	3 Yr. Tropical	555 (3.82)
#13 Kraft, Hardware	5 Yr. Tropical	531 (3.66)
#14 Kraft, Hardware	5 Yr. Controlled	519 (3.58)
#15 Kraft, Damaged	6 Mo. Tropical	525 (3.62)
#16 Kraft, Damaged	1 Yr. Tropical	530 (3.65)
#17 Kraft, Damaged	2 Yr. Tropical	583 (4.02)
#18 Kraft, Damaged	3 Yr. Tropical	488 (3.36)
#19 Kraft, Damaged	5 Yr. Tropical	485 (3.34)
#20 Kraft, Damaged	5 Yr. Controlled	507 (3.49)
#21 Kraft, No Sealant	1 Yr. Tropical	587 (4.04)
#22 Kraft, No Sealant	2 Yr. Tropical	526 (3.62)
#23 Kraft, No Sealant	3 Yr. Tropical	498 (3.43)
#24 Kraft, No Sealant	5 Yr. Tropical	531 (3.66)

TABLE 37

NOMEX PAPER CORE COMPRESSION STRENGTHS

Panel	Exposure	Avg. Strength psi (MPa)
#27 Nomex, Hardware	None	547 (3.77)
#27 Nomex, Hardware	6 Mo. Controlled	553 (3.81)
#29 Nomex, Damaged	None	503 (3.47)
#29 Nomex, Damaged	6 Mo. Controlled	504 (3.47)
#31 Nomex, No Sealant	1 Yr. Tropical	618 (4.26)
#25 Nomex, Standard	2 Yr. Tropical	584 (4.02)
#26 Nomex, Standard	5 Yr. Tropical	570 (3.93)
#28 Nomex, Hardware	5 Yr. Tropical	536 (3.69)
#30 Nomex, Damaged	5 Yr. Tropical	540 (3.72)
#32 Nomex, No Sealant	5 Yr. Tropical	569 (3.92)

performing compression tests on this area would be worthwhile. Therefore, compression specimens were machined with the holes centered in the 4-inch x 4-inch (10.2 x 10.2 cm) test area. After 3 years exposure the compression strengths obtained were 258 psi (1.8 MPa) for the hole in the top skin only and 405 psi (2.8 MPa) for the hole in the bottom skin. After 5 years exposure the strengths obtained were 302 psi (2.1 MPa) for the hole in the top skin only and 467 psi (3.2 MPa) for the hole in the bottom skin. The compression strengths measured on specimens taken from the same location for the panel stored for 5 years in the controlled environment are much higher, in particular the specimen with a hole in the top skin only. The results indicating the effect of simulated damage are shown in Table 38.

6.8 Flatwise Tension

The preparation and testing of the flatwise tension specimens caused the most difficulty of all the tests. The problems included the selection of adhesive to bond loading blocks, the number of loading blocks, the size of the muffle furnace to clean the blocks, and paint removal. During each visit to Panama one or more of these problems were solved and finally by the 2-year withdraw the tests proceeded without difficulty.

Flatwise tension test specimens were machined from each panel configuration. Except for hardware panels, each configuration is divided into quarters and at least three specimens are located in each of those quarters. The tensile tests were conducted at a crosshead rate of 0.03 inch (0.76 mm) per minute. Minimum values of tensile strength for honeycomb sandwich panels used in shelter construction have been established and are presented in ASTM 1091. The minimum flatwise tensile strength requirement is 306 psi (2.1 MPa). All of the tension specimens tested up to and including the 3-year tropical exposure exceed these minimum guidelines. The tensile specimens which had been stored in the laboratory for 6 months were not affected as were the compression specimens. After 5 years of tropical exposure, there was no downward trend in the flatwise tension results obtained. The summary of those results is presented in Tables 39 and 40.

6.8.1 Repair Patch

Each hardware configuration panel had a repair patch. The repair was done by the manufacturer of the panels at the time of original construction using techniques considered state of the art. There are no known guidelines or field tests to

TABLE 38

EFFECT OF SIMULATED DAMAGE ON COMPRESSION

Panel	Location	Exposure	Avg. Strength psi (MPa)	
#15 Kraft	"A" Hole Top Skin	6 Mo. Tropical	483 (3.33)	
#15 Kraft	"B" No Hole	6 Mo. Tropical	573 (3.95)	
#15 Kraft	"C" Hole Bottom Skin	6 Mo. Tropical	519 (3.58)	
#15 Kraft	"D" Hole Both Skins	6 Mo. Tropical	527 (3.63)	
#16 Kraft	"A" Hole Top Skin	1 Yr. Tropical	515 (3.55)	
#16 Kraft	"B" No Hole	1 Yr. Tropical	571 (3.93)	
#16 Kraft	"C" Hole Bottom Skin	1 Yr. Tropical	515 (3.55)	
#16 Kraft	"D" Hole Both Skins	1 Yr. Tropical	533 (3.67)	
#17 Kraft	"A" Hole Top Skin	2 Yr. Tropical	538 (3.71)	
#17 Kraft	"B" No Hole	2 Yr. Tropical	626 (4.31)	
#17 Kraft	"C" Hole Bottom Skin	2 Yr. Tropical	584 (4.02)	
#17 Kraft	"D" Hole Both Skins	2 Yr. Tropical	584 (4.02)	
#18 Kraft	"A" Hole Top Skin	3 Yr. Tropical	459 (3.16)	258 (1.78)(1)
#18 Kraft	"B" No Hole	3 Yr. Tropical	495 (3.41)	---
#18 Kraft	"C" Hole Bottom Skin	3 Yr. Tropical	498 (3.43)	405 (2.79)(1)
#18 Kraft	"D" Hole Both Skins	3 Yr. Tropical	501 (3.45)	342 (2.36)(1)
#19 Kraft	"A" Hole Top Skin	5 Yr. Tropical	476 (3.28)	302 (2.08)(1)
#19 Kraft	"B" No Hole	5 Yr. Tropical	480 (3.31)	---
#19 Kraft	"C" Hole Bottom Skin	5 Yr. Tropical	514 (3.54)	467 (3.22)(1)
#19 Kraft	"D" Hole Both Skins	5 Yr. Tropical	470 (3.24)	409 (2.82)(1)
#20 Kraft	"A" Hole Top Skin	5 Yr. Controlled	512 (3.53)	516 (3.56)(1)
#20 Kraft	"B" No Hole	5 Yr. Controlled	506 (3.49)	---
#20 Kraft	"C" Hole Bottom Skin	5 Yr. Controlled	515 (3.49)	502 (3.46)(1)
#20 Kraft	"D" Hole Both Skins	5 Yr. Controlled	493 (3.40)	477 (3.29)(1)

NOTE: 1. Compression specimens with simulated hole.

TABLE 39

KRAFT PAPER CORE FLATWISE TENSILE STRENGTHS

Panel	Exposure	Avg. Strength psi (MPa)
#1 Kraft, Standard	None	358 (2.47)
#1 Kraft, Standard	6 Mo. Controlled	353 (2.43)
#2 Kraft, Standard	6 Mo. Tropical	503 (3.47)
#3 Kraft, Standard	1 Yr. Tropical	394 (2.71)
#4 Kraft, Standard	2 Yr. Tropical	397 (2.74)
#5 Kraft, Standard	3 Yr. Tropical	485 (3.34)
#6 Kraft, Standard	5 Yr. Tropical	451 (3.11)
#7 Kraft, Standard	5 Yr. Controlled	429 (2.96)
#8 Kraft, Hardware	None	365 (2.51)
#8 Kraft, Hardware	6 Mo. Controlled	378 (2.60)
#9 Kraft, Hardware	6 Mo. Tropical	429 (2.96)
#10 Kraft, Hardware	1 Yr. Tropical	416 (2.87)
#11 Kraft, Hardware	2 Yr. Tropical	404 (2.78)
#12 Kraft, Hardware	3 Yr. Tropical	391 (2.69)
#13 Kraft, Hardware	5 Yr. Tropical	448 (3.09)
#14 Kraft, Hardware	5 Yr. Controlled	409 (2.82)
#15 Kraft, Damaged	6 Mo. Tropical	446 (3.07)
#16 Kraft, Damaged	1 Yr. Tropical	391 (2.69)
#17 Kraft, Damaged	2 Yr. Tropical	486 (3.35)
#18 Kraft, Damaged	3 Yr. Tropical	398 (2.74)
#19 Kraft, Damaged	5 Yr. Tropical	474 (3.27)
#20 Kraft, Damaged	5 Yr. Controlled	388 (2.67)
#21 Kraft, No Sealant	1 Yr. Tropical	470 (3.24)
#22 Kraft, No Sealant	2 Yr. Tropical	455 (3.13)
#23 Kraft, No Sealant	3 Yr. Tropical	500 (3.45)
#24 Kraft, No Sealant	5 Yr. Tropical	419 (2.89)

TABLE 40

NOMEX PAPER CORE FLATWISE TENSILE STRENGTHS

Panel	Exposure	Avg. Strength psi (MPa)
#27 Nomex, Hardware	None	361 (2.49)
#27 Nomex, Hardware	6 Mo. Controlled	378 (2.60)
#28 Nomex, Hardware	5 Yr. Tropical	409 (2.82)
#29 Nomex, Damaged	None	370 (2.55)
#29 Nomex, Damaged	6 Mo. Controlled	376 (2.59)
#30 Nomex, Damaged	5 Yr. Tropical	390 (2.69)
#31 Nomex, No Sealant	1 Yr. Tropical	410 (2.82)
#32 Nomex, No Sealant	5 Yr. Tropical	399 (2.75)
#25 Nomex, Standard	2 Yr. Tropical	414 (2.85)
#26 Nomex, Standard	5 Yr. Tropical	409 (2.82)

perform. It did seem appropriate to cut a flatwise tensile specimen directly over the patch and determine what effect solar and tropical exposure might have upon its strength. Table 41 presents the flatwise tension data obtained. The specimens from the control panel and after 6-month tropical exposure failed through what core remained after the repair. After 1-year tropical exposure the failure mode changed to debonding between the patch skin and the potting compound. Also, the strengths were reduced to less than 200 psi (1.38 MPa) and then less than 100 psi (0.69 MPa) after 2 years exposure. Since guidelines do not exist for the flatwise tensile strength of such a repair, it is not known whether this change in failure mode and reduced strength is significant. The tensile strength recovered somewhat after the 3- and 5-year tropical exposure. The tensile strength obtained from the repair patch in the controlled environment was very high, 755 psi (5.2 MPa). After failure it appeared that the quantity of repair adhesive used in applying this patch was significantly more than that used in other repairs. The tensile strength for the patches in the Nomex panels was essentially unchanged after 5 years exposure.

6.9 Beam Shear

The beam shear tests take the longest time to complete, due to the number of specimens and test speed. Once the test set-up was established during the first visit, all the tests went smoothly and failure modes were generally what was expected. Beam shear specimens were machined in both the "L" (ribbon) and "W" (transverse) direction of the honeycomb core. The panels were fabricated with the "L" direction of the honeycomb core running in the 8 ft. (2.4 m) length direction of each. Minimum values of beam shear strength for honeycomb sandwich panels used in shelter construction have been established and are presented in ASTM 1091. The minimum beam shear strength in the "L" direction is 180 psi (1.24 MPa) and in the "W" direction is 113 psi (0.78 MPa). All of the specimens tested have met these minimum guidelines. The beam shear values obtained for the specimens stored in the controlled laboratory for 6 months were slightly lower, about 10%, than the controls and the 6-month tropical. This reduction is evident for both Kraft paper and Nomex paper cores and in both the "L" and "W" directions. After 5 years of tropical exposure, no significant change in beam shear strength was observed. A summary of the beam shear results is presented in Tables 42 to 45.

TABLE 41
FLATWISE TENSION OF REPAIR PATCH

Panel	Exposure	Strength psi (MPa)
#8 Kraft	None	473 (3.26)
#9 Kraft	6 Mo. Tropical	300 (2.07)
#10 Kraft	1 Yr. Tropical	160 (1.10)
#11 Kraft	2 Yr. Tropical	80 (0.55)
#12 Kraft	3 Yr. Tropical	188 (1.30)
#13 Kraft	5 Yr. Tropical	139 (0.96)
#14 Kraft	5 Yr. Controlled	755 (5.20)
#27 Nomex	None	369 (2.54)
#28 Nomex	5 Yr. Tropical	331 (2.28)

TABLE 42

KRAFT PAPER CORE BEAM SHEAR, "L" DIRECTION

Panel	Exposure	Avg. Strength psi (MPa)
#1 Kraft, Standard	None	225 (1.55)
#1 Kraft, Standard	6 Mo. Controlled	204 (1.41)
#2 Kraft, Standard	6 Mo. Tropical	220 (1.52)
#3 Kraft, Standard	1 Yr. Tropical	247 (1.70)
#4 Kraft, Standard	2 Yr. Tropical	221 (1.52)
#5 Kraft, Standard	3 Yr. Tropical	227 (1.56)
#6 Kraft, Standard	5 Yr. Tropical	248 (1.71)
#7 Kraft, Standard	5 Yr. Controlled	213 (1.47)
#8 Kraft, Hardware	None	235 (1.62)
#8 Kraft, Hardware	6 Mo. Controlled	205 (1.41)
#9 Kraft, Hardware	6 Mo. Tropical	227 (1.56)
#10 Kraft, Hardware	1 Yr. Tropical	240 (1.65)
#11 Kraft, Hardware	2 Yr. Tropical	234 (1.61)
#12 Kraft, Hardware	3 Yr. Tropical	230 (1.58)
#13 Kraft, Hardware	5 Yr. Tropical	219 (1.51)
#14 Kraft, Hardware	5 Yr. Controlled	235 (1.62)
#15 Kraft, Damaged	6 Mo. Tropical	242 (1.67)
#16 Kraft, Damaged	1 Yr. Tropical	216 (1.49)
#17 Kraft, Damaged	2 Yr. Tropical	249 (1.72)
#18 Kraft, Damaged	3 Yr. Tropical	217 (1.50)
#19 Kraft, Damaged	5 Yr. Tropical	249 (1.72)
#20 Kraft, Damaged	5 Yr. Controlled	214 (1.47)
#21 Kraft, No Sealant	1 Yr. Tropical	251 (1.73)
#22 Kraft, No Sealant	2 Yr. Tropical	226 (1.56)
#23 Kraft, No Sealant	3 Yr. Tropical	234 (1.61)
#24 Kraft, No Sealant	5 Yr. Tropical	237 (1.63)

TABLE 43

KRAFT PAPER CORE BEAM SHEAR, "W" DIRECTION

Panel	Exposure	Avg. Strength psi (MPa)
#1 Kraft, Standard	None	138 (0.95)
#1 Kraft, Standard	6 Mo. Controlled	121 (0.83)
#2 Kraft, Standard	6 Mo. Tropical	129 (0.89)
#3 Kraft, Standard	1 Yr. Tropical	149 (1.03)
#4 Kraft, Standard	2 Yr. Tropical	134 (0.92)
#5 Kraft, Standard	3 Yr. Tropical	133 (0.92)
#6 Kraft, Standard	5 Yr. Tropical	144 (0.99)
#7 Kraft, Standard	5 Yr. Controlled	118 (0.81)
#8 Kraft, Hardware	None	137 (0.94)
#8 Kraft, Hardware	6 Mo. Controlled	120 (0.83)
#9 Kraft, Hardware	6 Mo. Tropical	148 (1.02)
#10 Kraft, Hardware	1 Yr. Tropical	137 (0.94)
#11 Kraft, Hardware	2 Yr. Tropical	150 (1.03)
#12 Kraft, Hardware	3 Yr. Tropical	157 (1.08)
#13 Kraft, Hardware	5 Yr. Tropical	145 (1.00)
#14 Kraft, Hardware	5 Yr. Controlled	151 (1.04)
#15 Kraft, Damaged	6 Mo. Tropical	132 (0.91)
#16 Kraft, Damaged	1 Yr. Tropical	130 (0.90)
#17 Kraft, Damaged	2 Yr. Tropical	149 (1.03)
#18 Kraft, Damaged	3 Yr. Tropical	136 (0.94)
#19 Kraft, Damaged	5 Yr. Tropical	140 (0.96)
#20 Kraft, Damaged	5 Yr. Controlled	140 (0.96)
#21 Kraft, No Sealant	1 Yr. Tropical	142 (0.98)
#22 Kraft, No Sealant	2 Yr. Tropical	128 (0.88)
#23 Kraft, No Sealant	3 Yr. Tropical	125 (0.86)
#24 Kraft, No Sealant	5 Yr. Tropical	146 (1.01)

TABLE 44

NOMEX PAPER CORE BEAM SHEAR, "L" DIRECTION

Panel	Exposure	Avg. Strength psi (MPa)
#27 Nomex, Hardware	None	268 (1.85)
#27 Nomex, Hardware	6 Mo. Controlled	250 (1.72)
#29 Nomex, Damaged	None	277 (1.91)
#29 Nomex, Damaged	6 Mo. Controlled	263 (1.81)
#31 Nomex, No Sealant	1 Yr. Tropical	317 (2.18)
#25 Nomex, Standard	2 Yr. Tropical	304 (2.09)
#26 Nomex, Standard	5 Yr. Tropical	291 (2.00)
#28 Nomex, Hardware	5 Yr. Tropical	289 (1.99)
#30 Nomex, Damaged	5 Yr. Tropical	284 (1.96)
#32 Nomex, No Sealant	5 Yr. Tropical	283 (1.95)

TABLE 45

NOMEX PAPER CORE BEAM SHEAR, "W" DIRECTION

Panel	Exposure	Avg. Strength psi (MPa)
#27 Nomex, Hardware	None	149 (1.03)
#27 Nomex, Hardware	6 Mo. Controlled	134 (0.92)
#29 Nomex, Damaged	None	149 (1.03)
#29 Nomex, Damaged	6 Mo. Controlled	138 (0.95)
#31 Nomex, No Sealant	1 Yr. Tropical	168 (1.16)
#25 Nomex, Standard	2 Yr. Tropical	158 (1.09)
#26 Nomex, Standard	5 Yr. Tropical	157 (1.08)
#28 Nomex, Hardware	5 Yr. Tropical	148 (1.02)
#30 Nomex, Damaged	5 Yr. Tropical	149 (1.03)
#32 Nomex, No Sealant	5 Yr. Tropical	151 (1.04)

6.10 Climbing Drum Peel

Climbing drum peel test specimens were machined from each panel configuration. Except for hardware panels, each configuration is divided into quarters and six specimens are located in each of those quarters. Three of these specimens were peeled with the 0.050 inch (1.3 mm) thick outside skin and three with the 0.040 inch (1.0 mm) thick inside skin. Of all the tests conducted on the honeycomb sandwich panels, the climbing drum peel was the most erratic. This is partly due to the fact that the climbing drum peel test recommends using more flexible skins than either of those used in shelter roof panels. ASTM D1781, "Climbing Drum Peel Test for Adhesives," suggests using a 0.020 inch (0.5 mm) thick skin rather than 0.040 or 0.050 inch (1.0 or 1.3 mm) which are used in shelter construction. There is, however, a suggested minimum value for climbing drum peel strength in shelter panels. This can be found in ASTM E874 and is 6.9 in.-lbs/in. (12.1 N/cm) of width. Unfortunately, this specification does not specify the skin thickness, but it is assumed to be 0.020 inch (0.5 mm). Regardless, not all of the average values for the Kraft paper core have met this minimum value. Even though the results are very erratic, it does appear that after 5 years of tropical exposure there is little effect upon the climbing drum peel properties obtained for both the 0.040 inch (1 mm) inside and the 0.050 inch (1.3 mm) outside skins. Also of note is that the cell size in the Nomex core is smaller than the cell size in the Kraft core. The smaller cell size yields higher peel strengths. This is an advantage when performing peel tests with thicker skins, at least if the failure is within the core. Since the loads are much higher, the thick skins are more likely to follow the contour of the drum. Therefore, the climbing drum peel results obtained for Nomex paper core are not only higher but also there is far less scatter. A summary of the climbing drum peel results obtained is presented in Tables 46 to 49.

6.11 Miscellaneous Results

Several tests were conducted which are identified as miscellaneous, but only because each did not generate the overwhelming quantity of data as the others. These tasks include insert pullout and torque. Inserts were potted into the inside and outside of each hardware panel. Upon withdrawal, each insert was tested for pullout and torque according to MIL-STD-907. All of the inserts passed the respective tests. Also, Shore "A" durometer was run on the polysulfide sealant on each panel upon withdrawal. The control and all panels up to and including 3-year tropical exposure had a Shore A

TABLE 46

KRAFT PAPER CORE CLIMBING DRUM PEEL, "L," INSIDE 0.040 INCH (1 mm) SKIN

Panel	Exposure	Avg. Peel in-lbs/in (N - cm/cm)
#1 Kraft, Standard	None	12.7 (56.5)
#1 Kraft, Standard	6 Mo. Controlled	10.2 (45.4)
#2 Kraft, Standard	6 Mo. Tropical	10.7 (47.6)
#3 Kraft, Standard	1 Yr. Tropical	10.2 (45.4)
#4 Kraft, Standard	2 Yr. Tropical	9.0 (40.0)
#5 Kraft, Standard	3 Yr. Tropical	9.1 (40.5)
#6 Kraft, Standard	5 Yr. Tropical	8.9 (39.6)
#7 Kraft, Standard	5 Yr. Controlled	11.5 (51.2)
#8 Kraft, Hardware	None	9.7 (43.1)
#8 Kraft, Hardware	6 Mo. Controlled	12.7 (56.5)
#9 Kraft, Hardware	6 Mo. Tropical	6.3 (28.0)
#10 Kraft, Hardware	1 Yr. Tropical	7.4 (32.9)
#11 Kraft, Hardware	2 Yr. Tropical	6.1 (27.1)
#12 Kraft, Hardware	3 Yr. Tropical	6.5 (28.9)
#13 Kraft, Hardware	5 Yr. Tropical	7.6 (33.8)
#14 Kraft, Hardware	5 Yr. Controlled	7.9 (35.1)
#15 Kraft, Damaged	6 Mo. Tropical	7.5 (33.4)
#16 Kraft, Damaged	1 Yr. Tropical	7.6 (33.8)
#17 Kraft, Damaged	2 Yr. Tropical	8.8 (39.1)
#18 Kraft, Damaged	3 Yr. Tropical	10.1 (44.9)
#19 Kraft, Damaged	5 Yr. Tropical	10.6 (47.1)
#20 Kraft, Damaged	5 Yr. Controlled	7.1 (31.6)
#21 Kraft, No Sealant	1 Yr. Tropical	12.7 (56.5)
#22 Kraft, No Sealant	2 Yr. Tropical	10.5 (46.7)
#23 Kraft, No Sealant	3 Yr. Tropical	12.8 (56.9)
#24 Kraft, No Sealant	5 Yr. Tropical	10.4 (46.3)

TABLE 47

KRAFT PAPER CORE CLIMBING DRUM PEEL,
"L," OUTSIDE 0.050 INCH (1.3 mm) SKIN

Panel	Exposure	Avg. Peel in-lbs/in (N - cm/cm)
#1 Kraft, Standard	None	9.7 (43.1)
#1 Kraft, Standard	6 Mo. Controlled	11.4 (50.7)
#2 Kraft, Standard	6 Mo. Tropical	9.9 (44.0)
#3 Kraft, Standard	1 Yr. Tropical	14.1 (62.7)
#4 Kraft, Standard	2 Yr. Tropical	11.9 (52.9)
#5 Kraft, Standard	3 Yr. Tropical	10.7 (47.6)
#6 Kraft, Standard	5 Yr. Tropical	10.6 (47.1)
#7 Kraft, Standard	5 Yr. Controlled	10.6 (47.1)
#8 Kraft, Hardware	None	4.1 (18.2)
#8 Kraft, Hardware	6 Mo. Controlled	9.0 (40.0)
#9 Kraft, Hardware	6 Mo. Tropical	8.3 (36.9)
#10 Kraft, Hardware	1 Yr. Tropical	7.1 (31.6)
#11 Kraft, Hardware	2 Yr. Tropical	13.0 (57.8)
#12 Kraft, Hardware	3 Yr. Tropical	10.6 (47.1)
#13 Kraft, Hardware	5 Yr. Tropical	7.7 (34.2)
#14 Kraft, Hardware	5 Yr. Controlled	10.4 (46.3)
#15 Kraft, Damaged	6 Mo. Tropical	14.0 (62.3)
#16 Kraft, Damaged	1 Yr. Tropical	15.3 (68.1)
#17 Kraft, Damaged	2 Yr. Tropical	15.2 (67.6)
#18 Kraft, Damaged	3 Yr. Tropical	13.8 (61.4)
#19 Kraft, Damaged	5 Yr. Tropical	16.6 (73.8)
#20 Kraft, Damaged	5 Yr. Controlled	15.4 (68.5)
#21 Kraft, No Sealant	1 Yr. Tropical	9.3 (41.4)
#22 Kraft, No Sealant	2 Yr. Tropical	13.9 (61.8)
#23 Kraft, No Sealant	3 Yr. Tropical	11.2 (49.8)
#24 Kraft, No Sealant	5 Yr. Tropical	7.9 (35.1)

TABLE 48

NOMEX PAPER CORE CLIMBING DRUM PEEL, "L" DIRECTION, INSIDE 0.040 INCH (1 mm) SKIN

Panel	Exposure	Avg. Peel in-lbs/in (N - cm/cm)
#27 Nomex, Hardware	None	14.8 (65.8)
#27 Nomex, Hardware	6 Mo. Controlled	19.9 (88.5)
#29 Nomex, Damaged	None	19.4 (86.3)
#29 Nomex, Damaged	6 Mo. Controlled	23.7 (105.4)
#31 Nomex, No Sealant	1 Yr. Tropical	23.8 (105.9)
#25 Nomex, Standard	2 Yr. Tropical	19.9 (88.5)
#26 Nomex, Standard	5 Yr. Tropical	18.2 (81.0)
#28 Nomex, Hardware	5 Yr. Tropical	12.3 (54.7)
#30 Nomex, Damaged	5 Yr. Tropical	19.3 (85.8)
#32 Nomex, No Sealant	5 Yr. Tropical	25.8 (114.8)

TABLE 49

NOMEX PAPER CORE CLIMBING DRUM PEEL, "L" DIRECTION, OUTSIDE 0.050 INCH (1.3 mm) SKIN

Panel	Exposure	Avg. Peel in-lbs/in (N - cm/cm)
#27 Nomex, Hardware	None	26.0 (115.6)
#27 Nomex, Hardware	6 Mo. Controlled	30.9 (137.4)
#29 Nomex, Damaged	None	26.5 (117.9)
#29 Nomex, Damaged	6 Mo. Controlled	34.7 (154.3)
#31 Nomex, No Sealant	1 Yr. Tropical	26.0 (115.6)
#25 Nomex, Standard	2 Yr. Tropical	25.7 (114.3)
#26 Nomex, Standard	5 Yr. Tropical	27.8 (123.7)
#28 Nomex, Hardware	5 Yr. Tropical	28.6 (127.2)
#30 Nomex, Damaged	5 Yr. Tropical	33.6 (149.5)
#32 Nomex, No Sealant	5 Yr. Tropical	28.2 (125.4)

durometer of 60 to 70. After 5 years tropical exposure the Shore A durometer was 50 to 60, but the panels in the controlled environment for 5 years remained 60 to 70. The sealant was also visually inspected for peeling or cracking and none was found.

6.11.1 Other Observations

During the visual inspection of the panels at Chiva-Chiva or Fort Clayton and the specimen testing in the TTC Materials Lab, several observations were made and include:

- Some of the core splice material did not expand the full height of the core.
- When testing peel, if a core splice happened to fall within the area of peel, often the failure mode would change and the peel force would usually go down.
- The panels were constructed as roof panels, which meant each has 1-inch foam pressed into the core. In some panels the core was in direct contact with the adhesive rather than 3/16 inch below the core surface as required.
- After 3 years exposure the foam in the simulated damage holes was slipping out the bottom side.

6.11.2 Results of Panel No. 32

During the 5-year tropic environment exposure only one panel actually had moisture visible in the interior during machining. That panel was No. 32, Nomex core, no polysulfide sealant, and which was exposed to the tropic environment for 5 years. During machining water could be seen in the lower edge of the panel, but not in the honeycomb core. Even after close examination it was not clear exactly where the water migrated through to the panel interior. The water was visible only in the lower edge of panel sections C and D. As soon as the specimens were machined, each was sealed in a plastic bag and delivered to the laboratory for test. When testing proceeded, panel 32 was the first tested. The results obtained for each test type in each quarter of the panel are shown in Table 50. The properties obtained are nearly the same in all sections of the panel and are similar to those obtained for other panels. The humidity indicators in each section remained blue. It is not certain how long the moisture was present in the panel. Regardless, it does show the importance of the polysulfide sealant.

TABLE 50

RESULTS OF PANEL NO. 32. NOMEX, NO SEALANT, 5-YEAR TROPIC EXPOSURE

Type Test Panel Section	Beam Shear (1) L, psi (MPa)	W, psi (MPa)	Drum Peel Thin Adherend(2) in-lb/in (N-cm/cm)	Thick Adherend (3) in-lb/in (N-cm/cm)	Flatwise Compression psi (MPa)	Flatwise Tension psi (MPa)
A	282 (1.94)	158 (1.09)	29.2(130.2)	26.2(116.8)	557 (3.84)	393 (2.71)
B	271 (1.87)	152 (1.05)	29.8(132.8)	30.3(135.1)	557 (3.84)	427 (2.94)
C (4)	296 (2.04)	148 (1.02)	23.9(106.5)	25.3(112.8)	612 (4.22)	366 (2.52)
D (4)	283 (1.95)	145 (1.00)	20.3(90.5)	30.9(137.8)	551 (3.78)	411 (2.83)

1. L = length of specimen in ribbon direction of honeycomb core
   W = length of specimen transverse to ribbon direction of honeycomb core

2. Thin adherend, 0.040 inch (1 mm), peeled off sandwich

3. Thick adherend, 0.050 inch (1.3 mm), peeled off sandwich

4. Moisture was visible in lower edge of "C" and "D."

6.12 Summary

The long-term tropic environmental exposure of rigid wall honeycomb sandwich panels performed at the U.S. Army Tropic Test Center in the Republic of Panama was a success. During the 5 years of exposure both the Kraft paper and Nomex honeycomb panels met all the specification minimum requirements, except for some isolated individual cases. In general, the panels performed extremely well.

The panels that were sealed with polysulfide sealant had an average weight gain of 0.33 pound (0.15 Kg) per panel. The unsealed panels picked up 1.02 pounds (0.46 Kg) of water. This shows how important it is to properly seal the panels. The polysulfide sealant durometer readings were all 60-70 Shore A except for the 5-year tropical exposure readings of 50-60.

Both the Kraft paper and Nomex panel flatwise tensile specimens had mainly core tearing failures. The Kraft paper honeycomb had an average strength of 424 psi (2.92 MPa), while the Nomex core was 389 psi (2.68 MPa). Both considerably higher than the 306 psi (2.11 MPa) minimum. There did not appear to be any degradation with time. In fact in this test and others the Kraft paper properties may have slightly increased due to further curing in the hot sun.

The climbing drum peel test was run on the 0.040 inch (1 mm) and 0.050 inch (1.3 mm) thick aluminum skins which are too thick for this test (a 0.020 inch (0.5 mm) skin is usually used). While the values obtained can be compared for the different exposure times, the thick facings caused the test data to exhibit high scatter (coefficient of variation of about 20 percent). The average Kraft paper peel torque was 10.3 in-lbs/in (45.8 Nm/m) and the average Nomex was 24.0 in-lbs/in (106.8 Nm/m). The smaller 1/4-inch (6.4 mm) Nomex cell size contributed to the higher peel torques for this core. Most failures for the Nomex samples were cohesive failures of the adhesive and partial honeycomb tearing. The specification minimum value is 6.9 in-lbs/in (30.7 Nm/m), which all but four sets passed. The torque values reported above were arrived at by subtracting the force required to bend the facing sheet and lift the drum from the total force measured during the test. There were no evidences of panel facing-to-core bond or honeycomb degradation with exposure time.

Average shear strength values for all the L-direction and W-direction beam shear specimens met the respective 180 and 113 psi (1.24 and 0.78 MPa) minimum

requirements. Most samples exhibited good core shear mode failures. The overall average Kraft paper shear strengths were 229 psi (1.58 MPa) (L) and 138 psi (0.95 MPa) (W), while the Nomex honeycomb values were 283 psi (1.95 MPa) and 150 psi (1.03 MPa), respectively. Again, neither honeycomb deteriorated with exposure.

The overall average compressive strengths were 528 psi (3.64 MPa) for the Kraft paper core and 552 psi (3.80 MPa) for the Nomex core. Both values were much higher than the 404 psi (2.78 MPa) minimum required. There was no evidence of honeycomb degradation with exposure time. The samples that had holes in just the top facing (this allowed water to be in the cells for up to 5 years) only had a slightly lower compressive strength. The Kraft paper core panels lost 17% and the Nomex honeycomb panels lost 6% of their strengths.

The biggest deteriorations apparent were the paint coming off the hinges and the patch bond to the panel facing. It was also noticed that in some samples the core splice adhesive had slumped down and was not the full 2-inch depth of the honeycomb.

In summary, if the panels are manufactured and sealed well, either the Kraft paper or Nomex panels should perform very well in a hot, humid climate. A detailed description of this project is presented in a separate technical report, WL-TR-91-4141.

7. TEST TECHNIQUES

Peel testing to determine adhesive bond strength is useful for quality control, as well as an evaluation aid for adhesive selection. Two commonly used peel tests are the Climbing Drum Peel (CDP) Test, ASTM D1781, and the Floating Roller Peel (FRP) Test, ASTM D3167. The climbing drum peel test is used primarily for bonded sandwich structure. It can, however, be used to evaluate metal-to-metal bonds. The floating roller peel test is used exclusively for metal-to-metal bonds.

Both of these tests are used in the characterization of materials employed in the construction and repair of tactical shelters. In both tests, the common practice is to use relatively thin (0.020 inch) (0.5 mm) aluminum as the peeling member of the bonded structure. Shelter construction, on the other hand, employs heavier gauge aluminum sheet, typically 0.032-0.050 inch (0.8-1.3 mm). One factor leading to the investigations described here was the concern as to whether the use of a thicker, and therefore less flexible, peeling member adversely affects the validity of peel test results.

A second factor raising a question in regard to peel testing was that the specimen failure behavior in an FRP test can vary considerably depending on the adhesive strength and the results are probably invalidated if an improper type of failure occurs.

Two investigations were carried out. The first concerned itself solely with the FRP test. It involved mathematical analysis and modeling of the FRP test, experimental confirmation of the mathematical model, and the development of a modified FRP test fixture design. It also attempted to develop an analytical procedure that could be used to avert undesirable failure behaviors. The second investigation focused on the CDP test. It largely paralleled the FRP study. The mathematical model of the flexible adherend deformation was modified to fit the case of CDP and experimental data were obtained to verify the model.

Each of these two studies will be discussed separately in the succeeding sections. Since both of these studies have been comprehensively reported in separate Air Force technical reports, cited at the end of the two succeeding sections, the summary overviews presented here are considerably abbreviated.

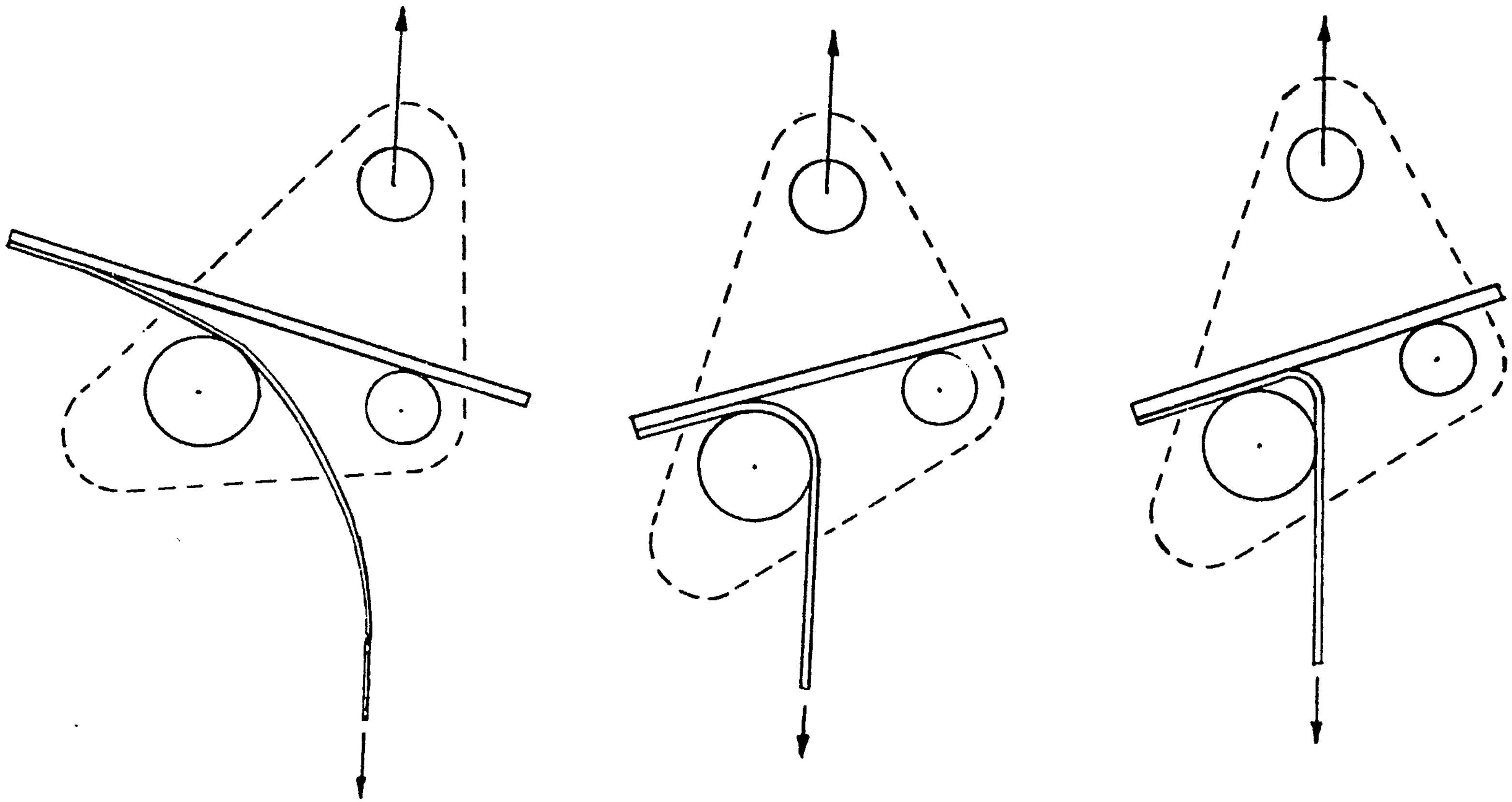
7.1 Floating Roller Peel Test

In ASTM Method D3167, the peel strength is determined by dividing the average peeling load by the specimen width. This procedure does not distinguish quantitatively between the percentage of the load required to fail the adhesive and the percentage of the load required to deform the flexible adherend. Rather, the total load necessary to both deform the flexible adherend and fail the adhesive is used to calculate the peel strength. It is apparent that variations in properties of the flexible adherend (yield stress, stiffness, thickness, etc.) will influence the test results. For this reason, this test method can at best be used for direct comparison of different adhesives only when specimen construction and conditions are identical. Even then, in the case of low peel strength adhesives, the load necessary to deform the flexible adherend is by far the major contributor to the total measured load and the ability of the procedure to discriminate between relatively weak adhesives becomes minimal.

Other problems can also occur when adhesives are tested in accordance with test method D3167. These are related to the fact that the test fixture does not adequately constrain the specimen. Figure 12 illustrates the three types of failure behavior that can occur in an FRP test.

For low ratios of adhesive peel strength to adherend stiffness, the unconstrained end of the specimen will rise, and the test fixture will rotate to compensate for the change in position of the specimen. The adhesive will begin to fail in cleavage rather than peel, causing the failure to occur well before the adherend translates over the roller. This is illustrated in Figure 12a. The measured loads for this situation will not only be low, but also spiked and erratic, characteristic of crack jump/arrest behavior, and one will frequently observe a load pattern in which the overall load recording diminishes continuously from start to finish of the test, with no portion ever approaching a constant load behavior. Figure 13 illustrates FRP results for both this type of behavior and for proper FRP behavior.

For high ratios of adhesive peel strength to adherend stiffness, the point of peel occurs between the two lower rollers of the test fixture, as illustrated in Figure 12c. For this case the measured load behavior will be similar to that illustrated in Figure 13b but will have greater numerical values.



(a) Weak-Adhesive Failure.

Cause: Flexible adherend is too stiff relative to peel strength of adhesive.

Solution: Use thinner flexible adherend and/or UDRI style PRP test fixture.

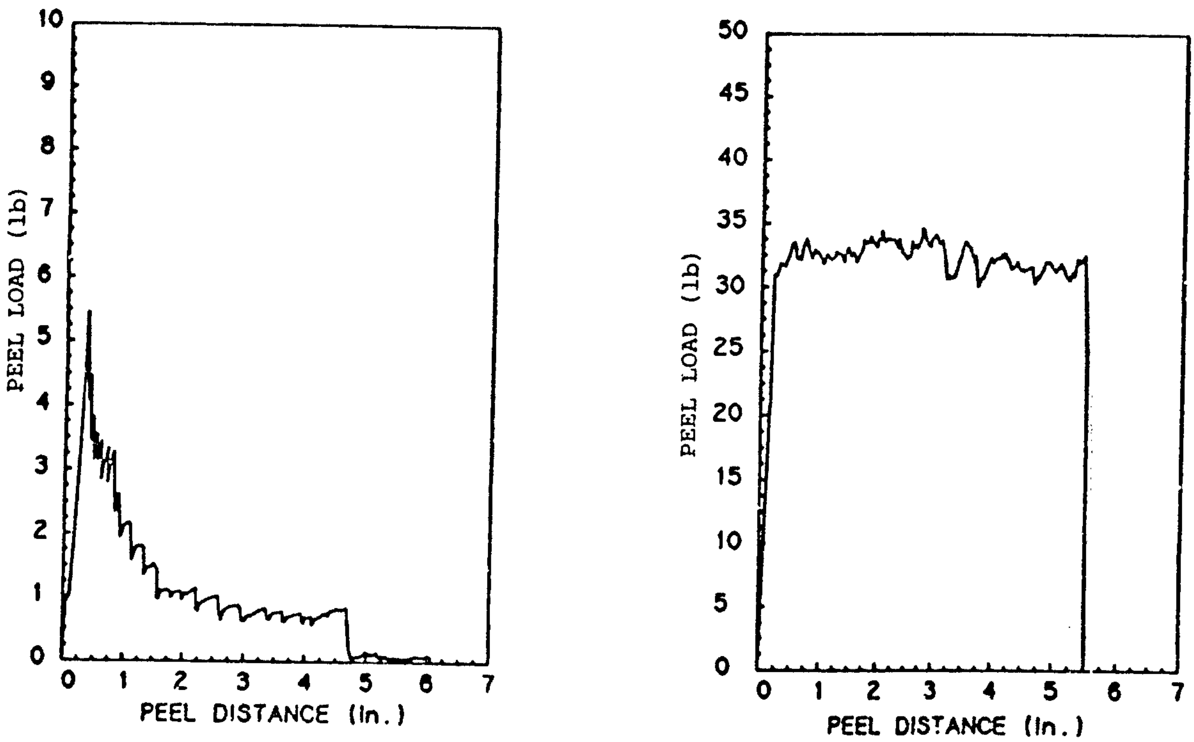
(b) Proper Failure.

(c) Strong-Adhesive Failure.

Flexible adherend is not stiff enough relative to peel strength of adhesive.

Use thicker flexible adherend.

Figure 12. Possilbe Failure Modes Encountered in Floating Roller Peel Test.



(a) FRP results for weak-adhesive type failure behavior (See Figure 12a).

(b) FRP results for proper failure behavior (See Figure 12b).

Figure 13. Typical FRP Test Results for Weak-Adhesive Type Failure and Proper Failure.

Neither of the two extreme behaviors illustrated in Figures 12a and 12c are desirable, nor do they produce reliable or valid FRP data. The D3167 specification states that "direct comparison of different adhesives can be made only when the angle of peel is identical," and this is the case only when the behavior illustrated in Figure 12b occurs. Thus, while the stated purpose in the introduction to D3167 is "to provide for the determination of the metal-to-metal peel strength of adhesives by a method that will provide good reproducibility at low, as well as high, strength levels ...," this is not achieved if the strength level is too low or too high.

As a result of these deficiencies, an investigation was undertaken to improve the accuracy and significance of the FRP test. An analytical model was developed which provides a means of interpreting and comparing test data independent of the test specimen construction. Using the analytical model, it is possible to distinguish between the percentage of the peel load required to fail the adhesive and the percentage needed to deform the flexible adherend. The model was found to exhibit good accuracy for a series of tests which encompassed several different flexible adherend thicknesses and materials. Design modifications were made to the ASTM peel test fixture described in D3167. The modified (UDRI type) test fixture eliminates the problems mentioned above for low peel strength adhesives and produce meaningful data. In order to avert the problem discussed above for high peel strength adhesives, an attempt was made to develop an analytical means of calculating the minimum flexible adherend thickness needed to insure that the proper failure behavior occurs. This was not altogether successful due to the uncertain effects of strain rate on the adhesive properties necessary as input data. Each of these efforts will be discussed in the following sections.

7.1.1 Modification of Test Fixture

The current ASTM peel test fixture illustrated in D3167 performs well for adhesives that are strong relative to the adherend stiffness. As the ratio of peel strength to adherend stiffness decreases, however, problems arise because the fixture does not adequately constrain the peel specimen. This was discussed earlier and illustrated in Figure 12a. To solve this problem, UDRI developed a modified test fixture that is able to adequately constrain the test specimen and avoid the problems encountered with the current ASTM peel fixture. The UDRI fixture, illustrated in Figure 14, has the following advantages:

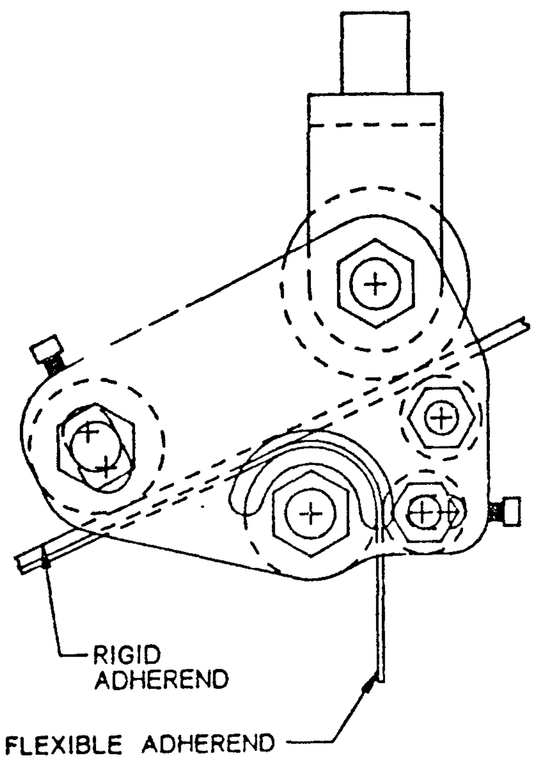


Figure 14. UDRI Test Fixture.

(1) one added roller prevents the free end of the test specimen from rising,

(2) the angle of peel is held constant,

(3) the adherend is forced to deform to the geometry of the roller (116.5° contact angle) by a second added roller,

(4) consistent peel loads can be measured for low ratios of adhesive strength to adherend stiffness, and

(5) the fixture is sensitive to small peel loads. With the UDRI fixture, however, the test specimens had to be constructed 1 inch longer than the length specified in D3167 so that a full 6 inches of peel could be accomplished while the end of the specimen was still constrained by the added roller.

Two experiments were conducted to compare the performance of the ASTM peel fixture and the UDRI fixture. One of the experiments involved bonding the flexible and rigid adherends together with intermittent segments of double-faced tape (Figure 15). The specimens were pulled through both fixtures at a rate of 6 inches (15.2 cm) per minute. It was expected that the plot of the peel force versus the distance peeled would look similar to Figure 16. The peel force was measured with both test fixtures. The experimental results are presented in Figure 17.

The results obtained using the current ASTM test fixture are spiked and inconsistent and do not correspond to the locations of either taped or gap segments as they pass through the fixture. It can be seen that after failure of the first piece of tape, the load decreases by about one-half. The second piece of tape is then loaded immediately before the 1-inch (2.54-cm) gap in the specimen has passed through the fixture. The specimen behaves in the manner illustrated in Figure 12a. It is impossible, from the measured data, illustrated in Figure 17a, to separate the load required to peel the adhesive from the load required to deform the adherend.

The results using the UDRI fixture, however, correspond reasonably well to the expected pattern (Figure 17b). The load required to peel the tape can be distinguished from the load required to deform the flexible adherend. Note that the loading is consistent from segment-to-segment, and the measured results are sensitive to small changes in load. In this particular case, one can conclude that a load of about 0.4 to 0.5 lbf (1.8-2.2 N) is required to peel the tape, with the remaining 4 lbf (17.8 N) being the work per unit length to deform the flexible adherend.

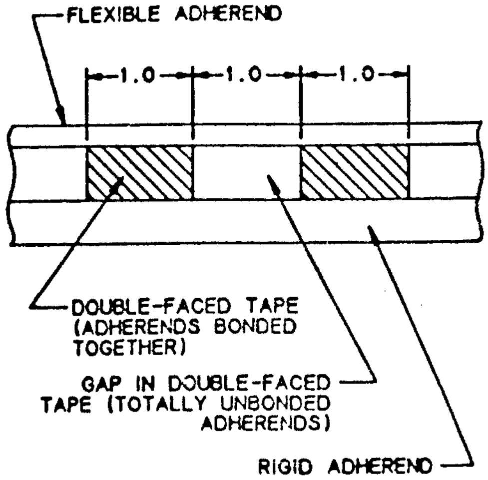


Figure 15. Specimen Design with Intermittent Adherend Bonding.

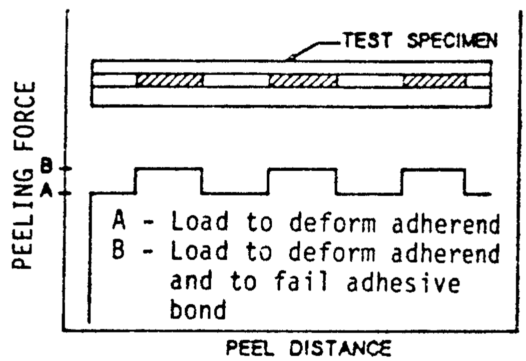


Figure 16. Expected Peel Results for Double-Faced Intermittent Tape.

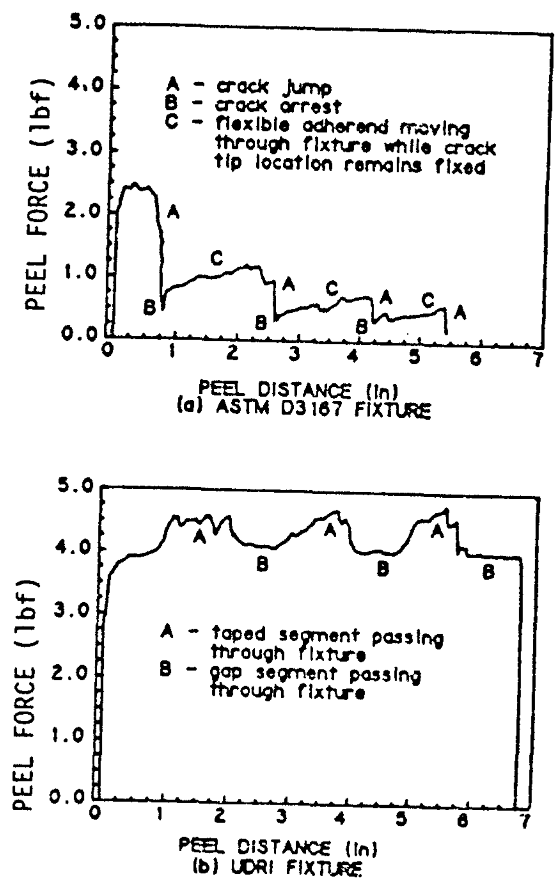


Figure 17. Peel Test Results with Intermittent Tape.

In the second experiment, a comparison was made between the two fixtures for test specimens bonded with a weak adhesive. The specimens were fabricated in accordance with the ASTM specifications, with 2024-T3 aluminum alloy (0.020 inch flexible adherend thickness and 0.062 inch ridge adherend thickness) and Versilok* 204 adhesive. The peel tests were conducted at -65°F (-54°C), at which temperature this adhesive has a relatively low peel strength. Several test specimens were peeled with each fixture in accordance with the ASTM test procedure. The results for a typical specimen are illustrated in Figure 18. The average force to peel the specimens was 0.88 lbf (3.9 N) using the ASTM fixture and 7.08 lbf (31 N) using the UDRI fixture.

As shown in the figure, the crack jump/arrest behavior and the diminishing load pattern are apparent for the old fixture, whereas the new fixture produces a more consistent load pattern. Experimental results similar to those discussed in the next section indicate that a force of 4.8 lbf (21.4 N) is required to deform a 0.020 inch (0.5 mm) adherend made from 2024-T3 aluminum alloy. The measured load when using the ASTM fixture, however, implies that a combined force of only 0.88 lbf (3.9 N) is required to both fail the adhesive and to deform the adherend. In contrast, the measured loads when using the UDRI fixture show that a combined force of 7.08 lbf (31.5 N) is needed to fail the adhesive and to deform the adherend. Of this measured load, the analytical model predicts that 4.23 lbf (18.8 N) and 2.85 lbf (12.7 N) are required to deform the adherend and to fail the adhesive, respectively. It is difficult, if not impossible, to apportion the measured load when using the ASTM fixture. Clearly, the data collected with the UDRI fixture is shown to be superior to that collected with the current ASTM fixture.

7.1.2 Mathematical Analysis of the FRP Test

The purpose of this analysis was to develop a model that would permit the calculation of the load required to deform the flexible adherend. This could then be subtracted from the total peeling load measured during a test to obtain the load that was required to fracture the adhesive.

The details of the development of this mathematical model are presented in detail in a separate Air Force technical report (AFWAL-TR-87-4082). For

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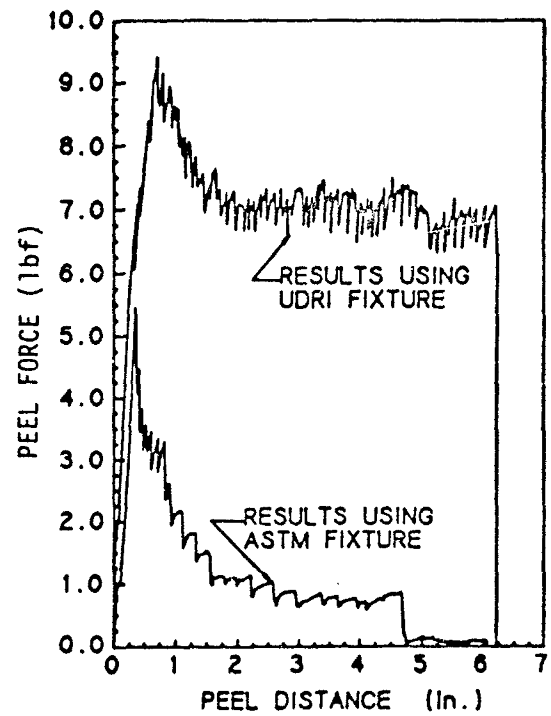

Figure 18. Comparison of Measured Peel Strengths of a Weak Adhesive at -65°F (-55°C).

this reason the model will not be further described here except for a discussion of the results.

Experimental peel tests were conducted with different flexible adherend materials and thicknesses to compare the results produced by the analytical model with actual collected data. In one of the two experiments, the UDRI fixture was used to measure the work per unit length required to deform the flexible adherend only; the rigid and flexible adherends were not bonded with an adhesive for this series of tests. In a second series of experiments, the adherends were bonded together with either a strong or weak adhesive. Identical specimens were pulled through either the UDRI fixture or the ASTM fixture to provide a comparison between the measured peel loads. An explanation of the experiments and a discussion of the results are presented below.

In the first experiment, flexible adherends were fabricated from 6061-T6 aluminum which varied in thickness from 0.010- to 0.040-inch (0.25-1.0 mm). Of the four specimens in each adherend group, three specimens of each group were approximately 1/2 inch (12.7 mm) wide, and the fourth was 1 inch (25.4 mm) wide. In order for the unbonded test specimens to translate through the UDRI fixture correctly, the rigid and flexible adherends were attached to each other at one end using tape. The tape acted like a rivet and prevented slipping between the rigid and flexible adherends. The specimens were then peeled as specified by D3167. The measured results are directly compared with results from the analytical model and are presented in Table 51.

The results generated using the analytical model are shown to agree with the experimental data. Typically, the analytical results are slightly lower than the experimental results, especially for the thicker adherends. This difference can be attributed to the assumption of small displacement theory. For the most part, the analytical results are within 5% of the experimental results. Only in 4 of the 20 cases tested did the analytical and experimental results disagree by over 5%, and in 3 of these the agreement was still within 9%.

In the second experiment, the rigid (thick) and flexible (thin) 6061-T6 adherends were bonded together with Versilok 204/17 adhesive (low peel strength at -67°F [-55°C]) and 3M 3564B/3559A adhesive (high peel strength at 72°F [22°C]). Four unprimed panels of each adhesive were fabricated. Two panels were constructed with a 0.020-inch (0.5-mm) flexible adherend and two panels were

TABLE 51

COMPARISON OF ANALYTICAL AND EXPERIMENTAL PEEL LOADS FOR VARIOUS ADHEREND STIFFNESSES(1)

MATERIAL: 6061-T6 BARE				
Thickness in (mm)	Width in (cm)	Stiffness lb-in (N-cm)	Experimentally Measured Load lb (N)	Load Calculated From Model lb (N)
0.010 (0.25)	0.510 (1.30)	0.451 (5.10)	0.463 (2.06)	0.487 (2.17)
0.010 (0.25)	0.507 (1.29)	0.448 (5.06)	0.446 (1.98)	0.484 (2.15)
0.010 (0.25)	0.508 (1.29)	0.449 (5.07)	0.452 (2.01)	0.485 (2.16)
0.010 (0.25)	1.01 (2.57)	0.892 (10.08)	0.806 (3.59)	0.964 (4.29)
0.015 (0.38)	0.510 (1.30)	1.520 (17.18)	2.044 (9.09)	1.897 (8.44)
0.015 (0.38)	0.507 (1.29)	1.517 (17.14)	1.986 (8.83)	1.893 (8.42)
0.015 (0.38)	0.508 (1.29)	1.514 (17.11)	1.913 (8.51)	1.890 (8.41)
0.015 (0.38)	1.01 (2.57)	3.011 (34.02)	3.785 (16.84)	3.757 (16.71)
0.020 (0.50)	0.500 (1.27)	3.533 (39.92)	4.270 (18.99)	4.172 (5.21)
0.020 (0.50)	0.495 (1.26)	3.498 (39.53)	4.074 (18.12)	4.130 (18.37)
0.020 (0.50)	0.493 (1.25)	3.484 (39.37)	4.045 (17.99)	4.114 (18.30)
0.020 (0.50)	1.020 (2.59)	7.208 (81.45)	8.558 (38.07)	8.511 (12.32)
0.025 (0.64)	0.505 (1.28)	6.963 (78.68)	7.653 (34.04)	7.478 (33.26)
0.025 (0.64)	0.503 (1.28)	6.936 (78.38)	7.623 (33.91)	7.448 (33.13)
0.025 (0.64)	0.505 (1.28)	6.970 (78.76)	7.767 (34.55)	7.478 (33.26)
0.025 (0.64)	1.030 (2.62)	14.216 (160.64)	15.748 (70.05)	15.252 (67.84)
0.040 (1.0)	0.500 (1.27)	28.267 (319.42)	22.712 (101.02)	22.493 (100.05)
0.040 (1.0)	0.507 (1.29)	28.662 (323.88)	23.337 (103.80)	22.809 (101.45)
0.040 (1.0)	0.507 (1.29)	28.662 (323.88)	23.079 (102.66)	22.808 (101.45)
0.040 (1.0)	1.000 (2.54)	56.533 (638.82)	45.117 (200.68)	44.984 (200.09)

(1) No actual peeling of an adhesive bond was occurring. The flexible adherend was simply being pulled through the UDRI peel test fixture.

constructed with a 0.040-inch (1-mm) flexible adherend. One of the two panels in each group was bonded with the Versilok and the other with the 3M adhesive. Each panel was cut into four test specimens which were 0.5 inch (12.7 mm) wide. Two of the specimens for each panel were tested using the ASTM fixture and the remaining two specimens were tested using the UDRI fixture. The specimens bonded with the Versilok adhesive were tested at a temperature of -67°F (-55°C) to induce the low peel strength behavior. The specimens bonded with the 3M adhesive were tested at room temperature. Results for the specimens bonded with the Versilok adhesive are presented in Table 52, while those for the 3M adhesive are summarized in Table 53.

In Table 52, which presents data for the low peel strength case, it can be observed that the measured values of the force required to peel the adhesive and to deform the adherend using the ASTM fixture are far below the experimental force required to deform only the adherend of the same thickness. When comparing the results for the specimens tested using the UDRI fixture with the experimental work per unit length required to deform the adherends, one can discriminate the portion of the total work required to fail the adhesive bond from that needed to deform the adherend. This discrimination cannot be made when using the ASTM fixture. One of the problems encountered in testing a low peel strength adhesive with the ASTM fixture is that the orientation of the specimen during the test does not conform to what is considered satisfactory behavior. This was illustrated in Figure 12a. The result of this behavior is that the deformation of the flexible adherend does not correspond to that upon which the model described in this paper was based. In fact, the work to deform the flexible adherend in this poorly behaved case is considerably less than that computed by our model because of the much larger radius of curvature through which the flexible adherend is deformed. Unfortunately, since the orientation, and concurrently the radius of curvature of the flexible adherend changes during the test, there is no way of accurately modeling the test.

One would expect that if the analytical model for the work to deform the flexible adherend is accurate, the resulting work to fail the bond would be independent of the flexible adherend thickness (or stiffness). It is evident from the data in Table 52 that this is not the case. One possible reason for this is the occurrence of different failure modes in specimens with different levels of flexible adherend thickness. All of the -67°F (-55°C) tests resulted in adhesive failure between the unprimed flexible adherend and the adhesive layer. Thus, the work to fail the adhesive bond, listed in the

TABLE 52

EXPERIMENTAL PEEL RESULTS FOR SPECIMENS BONDED WITH A LOW PEEL STRENGTH ADHESIVE

Adherend Material: 6061-T6 Bare Aluminum
Adhesive: Versilok 204/17
Test Temperature: -67°F (-55°C)

Specimen Number	Thickness of Flexible Adherend in (mm)	Test Fixture	Experimental W' to Deform Adherend and Fail Adhesive Bond, lbf (N)	Analytical W' to Deform the Adherend Only* lbf (N)	W' to Fail Adhesive Bond (Column 4 - Column 5) lbf (N)
1	0.020 (0.5)	ASTM	1.95 (8.67)	4.17 (18.55)	-2.22 (-9.87)+
2	0.020 (0.5)	ASTM	0.37 (1.65)	4.17 (18.55)	-3.80 (-16.9)+
3	0.020 (0.5)	UDRI	5.03 (22.37)	4.17 (18.55)	0.86 (3.83)
4	0.020 (0.5)	UDRI	5.06 (22.51)	4.17 (18.55)	0.89 (3.96)
1	0.040 (1.0)	ASTM	4.09 (18.19)	22.49 (100.04)	-18.4 (-81.84)+
2	0.040 (1.0)	ASTM	4.19 (18.64)	22.49 (100.04)	-18.3 (-81.40)+
3	0.040 (1.0)	UDRI	24.78 (110.22)	22.49 (100.04)	2.29 (10.19)
4	0.040 (1.0)	UDRI	24.84 (110.49)	22.49 (100.04)	2.35 (10.45)

* From Table 51 for 0.500 inch (12.9 mm) width

+Negative values are meaingless and reflect the unsuitability of the test for this set of conditions.

TABLE 53

EXPERIMENTAL PEEL RESULTS FOR SPECIMENS BONDED WITH A HIGH PEEL STRENGTH ADHESIVE

Adherend Material: 6061-T6 Bare Aluminum
Adhesive: 3M 3564B/3559A
Test Temperature: 72°F (22°C)

Specimen Number	Thickness of Flexible Adherend in(mm)	Test Fixture	Experimental W' to Deform Adherend and Fail Adhesive Bond, lbf (N)	Analytical W' to Deform the Adherend Only* lbf (N)	W' to Fail Adhesive Bond (Column 4 - Column 5) lbf (N)
1	0.020 (0.5)	ASTM	31.81 (141.49)	Avg. 4.17 (18.55)	27.64 (122.94)
2	0.020 (0.5)	ASTM	33.65 (149.68)	Avg. 4.17 (18.55)	29.48 (131.13)
3	0.020 (0.5)	UDRI	30.76 (136.82)	Avg. 4.17 (18.55)	26.59 (118.27)
4	0.020 (0.5)	UDRI	30.61 (136.15)	Avg. 4.17 (18.55)	26.44 (117.61)
1	0.040 (1.0)	ASTM	42.22 (187.79)	Avg. 22.49 (100.04)	19.73 (87.76)
2	0.040 (1.0)	ASTM	43.23 (192.29)	Avg. 22.49 (100.04)	20.74 (92.25)
3	0.040 (1.0)	UDRI	43.30 (192.60)	Avg. 22.49 (100.04)	20.81 (92.56)
4	0.040 (1.0)	UDRI	42.23 (187.84)	Avg. 22.49 (100.04)	19.74 (87.80)

* From Table 51 for 0.500-inch (12.7-mm) width.

last column of Table 52, is actually the work to fail the interface rather than the adhesive itself. Since the values for both the thin and thick adherend cases are low, it is felt that relatively minor differences in surface preparation could readily account for the difference in the results.

Table 53 contains the results for test specimens which were bonded with the 3M 3564B/3559A adhesive. For this case, in which the peel strengths are relatively high, the results using the UDRI fixture and the ASTM fixture were approximately the same for equivalent adherend thicknesses. This verifies that the design changes made on the test fixture do not influence the experimental results for specimens that behave properly. Note that in this series of tests, one can discriminate between the work required to deform the adherend and the work needed to fail the adhesive bond for both test fixtures. Again, there appears to be a discrepancy between the adhesive peel strength measured with the 0.020-inch (0.5-mm) adherend specimens and the 0.040-inch (1-mm) adherend specimens in that one would expect the adhesive peel strengths (W' to fail the adhesive) to be equal regardless of the adherend thickness. This seeming inconsistency in the peel strength of the adhesive, however, is related to the fact that an improper failure mode of the type illustrated in Figure 12c is occurring on the specimens with the 0.020-inch (0.5-mm) flexible adherends. As a result of this failure behavior, the radius of curvature of 0.020-inch (0.5-mm) adherend is less than that of the roller. This, in turn, increases the strain state in the material. Increases in the strain will also increase the force required to deform the adherend. Thus, the analytically calculated W' to deform the 0.020-inch (0.5-mm) adherend in column 5 of Table 53 is too low, causing the value of W' in column 6 for the adhesive failure to be too high. In contrast, the peel strengths for the specimens with 0.040-inch (1-mm) adherends were lower because the specimens failed in the proper mode during the test. Thus, this apparent discrepancy is not related to the model, but instead is the result of an imbalance in the ratio of the adhesive strength to the adherend stiffness. The indicated increase in the peel strength of the adhesive for the 0.020-inch (0.5-mm) adherend specimens is actually a result of the additional force required to deform the flexible adherend to a radius less than the radius of the roller.

7.1.3 Proper Sizing of Flexible Adherend

It will be recalled from Figure 12 that two undesirable failure modes can occur in an FRP test, one for the case in which the adhesive is too weak relative to the stiffness of the flexible adherend and one for the case in which the adhesive is too strong. The former case can be prevented by using the UDRI-type modified FRP test fixture. The latter case could not be solved by further modification of the test fixture. The alternative is to choose an adherend thickness such that detachment always occurs while the adherend is conformed to the roller surface.

As noted in Figure 12, the avoidance of improper failure modes in an FRP test requires that the thickness (or stiffness) of the flexible adherend be neither too low nor too high relative to the peel strength of the adhesive being tested. One approach to identifying a flexible adherend thickness that will produce the failure mode illustrated in Figure 12b is through trial and error. An alternate approach would be to develop an analytical procedure that would enable one to compute the satisfactory adherend thickness in advance using readily available data for the adherend and adhesive. The latter approach, if successful, would eliminate the necessity to carry out a trial and error procedure before preparation of satisfactory test specimens. This latter approach was undertaken and resulted in an analytical model designated the Maximum Cleavage Stress (MCS) Criterion. This analysis yields the minimum adherend thickness required to insure that the strong-adhesive type failure behavior illustrated in Figure 12c is avoided. The input material property data required for this analysis are the Young's moduli of the adherend and adhesive, yield strength of adherend, and tensile strength of adhesive. One problem with using manufacturer's data for the adhesive properties, however, it that the manufacturer's data were most likely obtained at a significantly lower strain rate (by two orders of magnitude) than that encountered in an FRP test. Strain rates of the magnitude encountered in an FRP test have been shown [4,5] to result in a doubling of tensile strength over that measured in a static test. In addition to this increase in measured tensile strength, Young's modulus is also raised by strain rates such as these. The net result of this strain rate effect is that the adhesive tensile strength value used in the MCS criterion must be between two and three times the quasi-static tensile strength in order for the criterion to accurately predict the minimum adherend thickness to avert the strong-adhesive type failure mode illustrated in Figure 12c.

7.1.4 Extra Energy to Deform a Nonconforming Adherend

An effort was also undertaken to analytically compute the extra deformation energy absorbed by the flexible adherend in the event of a strong-adhesive type failure mode illustrated in Figure 12c. Experimental data indicated that the model for computing this extra deformation energy appeared to be quite reasonable. Thus, one could, using this model, extract a reasonably pure adhesive peel strength from an FRP test even in the case of the type failure mode illustrated in Figure 12c.

A much more detailed discussion of the derivation of the Maximum Cleavage Stress Criterion (to compute minimum adherend thickness to avert strong-adhesive type failure modes) and the methodology to account for the extra energy expended in deforming the adherend if it does not conform to the roller is presented in Air Force report WL-TR-91-4086.

7.1.5 Summary of FRP Test Investigation

As a result of this investigation, the following conclusions were reached:

(a) An analytical model was developed that is able to discriminate the work per unit length required to deform the flexible adherend from the work per unit length needed to fail the adhesive. The model agreed with the experimental results for the two aluminum alloys that were tested. The vast majority of the analytical results were within 5% of the experimental results.

(b) As a result of the deficiencies of the current ASTM test fixture, the University of Dayton Research Institute designed a modified test fixture to eliminate the existing problems when peeling low strength adhesives. The UDRI fixture adequately constrains the test specimen so that consistent results can be measured regardless of test specimen construction and test conditions. The UDRI fixture provides the capability of measuring a meaningful peel strength for the low peel strength adhesives. Experimental data collected with the UDRI fixture proved to be superior to the current ASTM fixture.

(c) While the principal thrust of the test fixture redesign effort in this investigation was to overcome undesirable failure modes with low peel strength adhesives, undesirable failure modes can also occur with high peel strength adhesives. Avoidance of both these undesirable failure modes requires that a balance between adhesive peel strength and adherend stiffness

be maintained in order for an FRP test to produce consistent and known failure modes and meaningful test results.

(d) The Maximum Cleavage Stress Criterion, as a first order estimate, appears to reasonably predict the minimum flexible adherend thickness in FRP and CDP tests if strain rate effects are accounted for. The predicted thicknesses are particularly sensitive to the glueline thickness and strength of the adhesive, and to the yield strength of the adherend material.

(e) The bulk tensile strength of the adhesive utilized in the calculations appears, from the literature, to be highly dependent on strain rate. Since manufacturer's data consists of data derived from quasi-static tests, and peel tests are run considerably faster, the tensile strengths used in minimum thickness calculations need to be increased. Factors in this study range from just over two to three times. Values of this magnitude agree with strength increases reported in the literature.

(f) The additional energy consumed by adherends which do not conform to the roller surface may be calculated in order to compare peel strengths with adherends which do. However, results may still differ slightly since failure modes are slightly different. In addition, this calculation requires collection of additional data to measure the geometry of the non-conforming adherend. This may not be desirable in some cases.

(g) The "% Work" of the adherend can be used as a diagnostic tool to determine if adherends are indeed conforming. Adherend deformation accounts for 60-75% of the test load measured in a bonded sample if the adherend has conformed. If it has not, the adherend will appear to account for less energy, 20-50%.

7.2 Climbing Drum Peel Test

The Climbing Drum Peel (CDP) Test (ASTM D1781-76) consists of debonding a metal skin from a honeycomb core sandwich specimen in a peeling mode by wrapping the skin around a drum that traverses the length of the specimen during the test. A portion of the load, or torque, required to pull the drum along the length of the specimen, however, actually goes into wrapping the skin around the drum after it has detached from the core. The portion of the total load going into this plastic and permanent deformation of the skin must be accounted for so that reported "peel strengths" are not artificially high. The torque to wrap the skin around the drum must either be calculated or measured, and must be subtracted from torques measured for actual bonded specimens. Traditionally this has been measured by fastening a section of unbonded skin material in the test fixture and running the test to generate a calibration

torque. This value is then subtracted from the torque determined in the test of a bonded specimen, with the difference being considered the adhesive peel torque or peel "strength."

For the purposes of generating comparative adhesive properties, D1781 suggests using 0.020-inch (0.5-mm) thick aluminum as the peeling skin material. In tactical shelter construction, however, skin thicknesses in the 0.032-0.050 inch (0.8-1.3 mm) range are commonly used. One of the questions giving rise to this investigation of the CDP test was whether the use of a heavier guage skin than was specified could invalidate the test results.

In the case of 0.040-inch (1 mm) aluminum skins, a load of approximately 100 lbf (445 N) is required to wrap the skin around the drum. This compares to a total of approximately 130 lbf (578 N) for bonded honeycomb sandwich panels. Thus, it is evident skin deformation alone accounts for around 75% of the total measured load, and the adhesive peel strength is the difference between two relatively large numbers. This is an undesirable situation at best, because a relatively small error in one of the larger measured numbers produces a relatively large error in the difference (the "adhesive peel strength").

In addition to the occasional desire to test specimens with skin thicknesses larger than that suggested in D1781, the skin material (and consequently the stiffness) also varies from application to application. If specimens representative of the actual application are tested, one can encounter wide variations in the relative torque needed to wrap the various types and thicknesses of skin around the drum. The effects of these differences are not thoroughly addressed in D1781.

It will be recalled from the discussion of the FRP test in Section 7.1 that two undesirable failure behaviors could occur (Figure 12). In one case the cause was due to the fact that the skin was too stiff relative to the adhesive strength (weak-adhesive type failure behavior, Figure 12a), while in the other case the reverse occurred (strong-adhesive type failure, Figure 12c). The fixturing employed in the CDP test prevents the weak-adhesive type behavior. The strong-adhesive type failure, however, can occur in the CDP test as well as in the FRP test.

The analyses developed and experience gained in the study of the FRP test were extended to the case of the CDP test and are described in the succeeding sections.

7.2.1 Mathematical Analysis of the CDP Test

The analytical approach used to model adherend deformation in an FRP test (discussed in Section 7.1.2) was applied to the case of the CDP test. The details of this analytical procedure are presented in Air Force technical report WL-TR-91-4086 and will not be presented here. Suffice to say that analysis of the CDP test is simpler than that of the FRP test because the flexible adherend does not straighten out as the test progresses as it does in an FRP test. This analytical model produces torque values to wrap the unbonded skin around the drum that are in close agreement with experimentally measured torques. Table 54 lists these results.

TABLE 54

CLIMBING DRUM PEEL CALIBRATION RESULTS (1)

Sample	Material	Thickness in (mm)	Measured Force to Deform Adherend lbf (N)	Analytically Predicted Force lbf (N)
1	2024-T3	0.040 (1)	102.5 (456)	99.85 (444)
2	2024-T3	0.040 (1)	102.4 (455)	99.85 (444)
3	2024-T3	0.040 (1)	101.3 (451)	99.85 (444)
4	2024-T3	0.020 (0.5)	33.28 (148)	36.81 (164)
5	2024-T3	0.020 (0.5)	33.38 (148)	36.81 (164)
6	2024-T3	0.020 (0.5)	33.65 (150)	36.81 (164)

NOTE: (1) Wrapping of unbonded skins around climbing drum.

It is evident from the data in Table 54 that the analytical procedure slightly underestimates (by about 2%) the force required to deform the 40 mil (1 mm) adherends and slightly overestimates (by about 10%) the force to deform the 20 mil (0.5 mm) adherends.

CDP tests were performed on four different sets of bonded honeycomb sandwich specimens that were prepared with two different adhesives and two different skin thicknesses. Table 55 presents these results. On average, the use of the analytically predicted calibration force produced adhesive peel strength values that were within 7% of the values obtained by using the measured calibration force. This is very good agreement.

As was the case in FRP testing, a discrepancy appears in the data of Table 55 for the torque required to fracture the adhesive for different adherend thicknesses. Ideally, the torque required to fracture the adhesive is independent of the adherend thickness, since the use of calibration specimens, or calibration force calculations, accounts for the additional torque to deform the adherend. Table 55 also reveals a related fact: the calibration force accounts for roughly 75% of the measured force in bonded specimens with 0.040 inch (1 mm) skins, while it accounts for only 36% of the force in specimens with 0.020 inch (0.5 mm) skins.

TABLE 55
CLIMBING DRUM PEEL STRENGTH RESULTS (1)

Adhesive	Adherend Thickness in (mm)	Measured Peel Force lbf (N)	Torque to Fracture Adhesive in-lb/in (N-cm/cm)	
			Measured (2)	Closed Form (3)
Hysol EA9628	0.020 (0.5)	88.38 (393)	9.12 (40.6)	8.42 (37.5)
Hysol EA9628	0.040 (1.0)	126.0 (560)	3.89 (17.3)	4.18 (18.6)
American Cyanamid FM300K	0.020 (0.5)	94.79 (422)	10.16 (45.2)	9.47 (42.1)
American Cyanamid FM300K	0.040 (1.0)	137.2 (610)	5.67 (25.2)	5.98 (26.6)

(1) Each row represents average of three tests.
(2) Using measured Peel Force and an average of the three measured Calibration Forces (Table 54) for each thickness.
(3) Using measured peel force and Estimated Calibration Force (Table 54) for each adherend thickness.

Visual inspection of the test specimens with 0.020 inch (0.5 mm) adherends revealed "kinked" or "crimped" zones which align with the regions between columns of cells. The zones, appearing in reflected light as dark bands across the width of the adherend, are areas in which greater plastic deformation occurred. This increased deformation suggests that, at these points, the adherend pulled away from the climbing drum in order to transfer sufficient load to fracture the adhesive. The larger curvatures necessary to transfer sufficient load result in higher measured forces. As in the floating roller peel test, the behavior represents a different failure mode than in the specimens with thicker adherends which remain conformed to the roller, and results in higher

apparent peel strength. This behavior is similar to that illustrated in Figure 12c for the FRP behavior.

7.2.2 Proper Sizing of Flexible Adherend

The MCS Criteria for minimum adherend thickness, if valid, should predict the above results. Table 56 shows the predicted minimum thicknesses for the bonded CDP tests for a range of typical glueline thicknesses. Given that the sample glueline thicknesses are generally 0.007-0.010 inch (0.18-0.25 mm), and the minimum adherend thickness to assure perfect conformance to the drum surface is 0.020-0.040 inch (0.5-1 mm) (since 0.040-inch (1-mm) specimens conformed, while 0.020-inch (0.5-mm) specimens did not), the predictions are too low.

TABLE 56

MINIMUM ADHEREND THICKNESS PREDICTIONS*

			Minimum Adherend Thickness in (mm) for Adhesive Strength of	
Adhesive	σ_0 = Bulk Tensile Strength psi (MPa)	Glueline Thickness in (mm)	σ_0	$2\sigma_0$
EA9628	7500 (51.7)	0.005 (0.13)	0.0158 (0.40)	0.0323 (0.82)
		0.007 (0.18)	0.0179 (0.45)	0.0421 (1.1)
		0.010 (0.25)	0.0210 (0.53)	0.0574 (1.5)
		0.020 (0.50)	0.0320 (0.81)	0.170 (4.3)
FM300K	5500 (37.9)	0.005 (0.13)	0.0134 (0.34)	0.0216 (0.55)
		0.007 (0.18)	0.0145 (0.37)	0.0263 (0.67)
		0.010 (0.25)	0.0161 (0.41)	0.0338 (0.86)
		0.020 (0.50)	0.0216 (0.55)	0.0605 (1.5)

* 2024-T3 Aluminum Skins

This is the same result seen in the FRP predictions. It would appear that strain rate probably has an effect on the strength and modulus of the adhesive, as the CDP test is conducted at stroke rates similar to the FRP. However, since the CDP drum diameter is larger than the FRP roller diameter, and since the strain rate at the crack front is inversely proportional to the radius around which the adherend is being bent, the effect should be less pronounced in the CDP test. Table 56 shows this to be the case, as the required increase in adhesive strength is between one and two times. FRP tests showed this value to be between two and three times. These results validate the use of the MCS Criterion for predicting minimum adherend thickness to assure conformance to the drum.

7.2.3 Extra Energy to Deform a Nonconforming Adherend

Although it would be possible to calculate the additional energy expended in the deformation of non-conforming skins, this procedure was not implemented for the CDP test as it was for the FRP test (Section 7.1.4). A simple means for mounting a stationary grid (for angle measurements) to the test fixture could not be found in a timely manner. From visual inspection during the test, the distance the skin pulled away from the drum was very small compared to the non-conforming FRP adherends. Estimations of additional deformation energy without the benefit of a reference grid would be difficult. A means for making angle measurements needs to be developed before accurate data can be obtained.

A much more detailed discussion of the use of the MCS Criterion to compute the minimum flexible adherend thickness to insure perfect adherend compliance to the drum during a CDP test is presented in Air Force report WL-TR-91-4086. This report also presents experimental data that demonstrates the accuracy of an analytical model to compute the torque required to wrap an unbonded skin around the drum (the calibration torque).

7.2.4 Summary of CDP Test Investigation

The following conclusions were made for the case of CDP testing.

(a) The calibration loads in a CDP test can be accurately calculated (to within an average of 7% for the adherends tested in this study) with a simple equation, eliminating the need for the testing of dummy samples.

(b) CDP results suggest that the 20 mil (0.5 mm) adherend thickness suggested by ASTM D1781-76 is inappropriate for higher peel strength adhesives. The implication of this extends to more than just the use of CDP to compare two different adhesives, one of which may be strong and one weak. It also applies to the case of a single adhesive that may be weak at low temperature but strong at ambient or elevated temperature.

(c) The Maximum Cleavage Stress Criterion, as a first order estimate, appears to reasonably predict the minimum flexible adherend thickness in CDP tests if strain rate effects are accounted for. The predicted thicknesses are particularly sensitive to the glueline thickness and strength of the adhesive, and to the yield strength of the adherend material.

(d) The bulk tensile strength of the adhesive utilized in the calculations appears, from the literature, to be highly dependent on strain rate. Since manufacturer's data consists of data derived from quasi-static tests, and CDP tests are run considerably faster, the tensile strengths used in minimum thickness calculations need to be increased. Factors in this study range from just over one to two times. Values of this magnitude agree with strength increases reported in the literature.

(e) As was the case for FRP testing, the additional energy consumed by adherends which do not conform to the drum could be calculated in order to compare peel strengths with adherends which do. This calculation, however, requires collection of additional data to measure the geometry of the non-conforming adherend. This may not be desirable in some cases.

8. REPAIR AND REDEPLOYMENT

8.1 Design, Development, and Demonstration of an Easy-Fix Method for Redeploying Damaged Tactical Shelters

Tactical shelters are susceptible to a variety of types of in-service damage. This can result from battle damage, handling/transport damage, and environmental damage, and can be of a structural or functional nature. Structural damage consists of damage of sufficient extent to walls, roof, floor, or frame that transportability of the shelter is jeopardized. EASY-FIX is a concept for providing the means to evacuate structurally damaged, no longer operational shelters using helicopter external airlift capabilities.

Two activities were undertaken in this area. The first was to design, fabricate and demonstrate a prototype hardware system applicable to the S-280 shelter. The second was to investigate the feasibility of developing a similar system for the ISO shelter.

8.1.1 Easy-Fix System for S280 Shelter

The objective of this effort was two-fold: first, to design and fabricate a hardware system to meet the EASY-FIX requirements, and second, to demonstrate the use of this hardware on a government-furnished S-280 B/G shelter (basic nominal dimensions 12 feet long, 7.5 feet wide, and 7.5 feet high). Each of these objectives was accomplished. A technical report, AFWAL-TR-87-4115, was published that describes and details the ground rules, design approach, components, assembly, and demonstration testing of the Easy-Fix hardware system. The easy assembly of the system was demonstrated and a fully loaded S-280 B/G shelter was lifted with the system. Figure 19 presents a schematic illustration of the Easy-Fix system and Figure 20 illustrates the system in place on a shelter during the fully loaded demonstration test.

8.1.2 Easy-Fix System for ISO Shelter

A preliminary investigation was undertaken to define structural concepts, materials systems, and assembly procedures applicable to the development of an airlift system for heavily damaged ISO shelters. A conceptual system, similar to that developed for the S2800 shelter and discussed in Section 8.1.1, was defined for ISO shelters. Since ISO shelters are larger and heavier than S280B shelters, the Easy-Fix

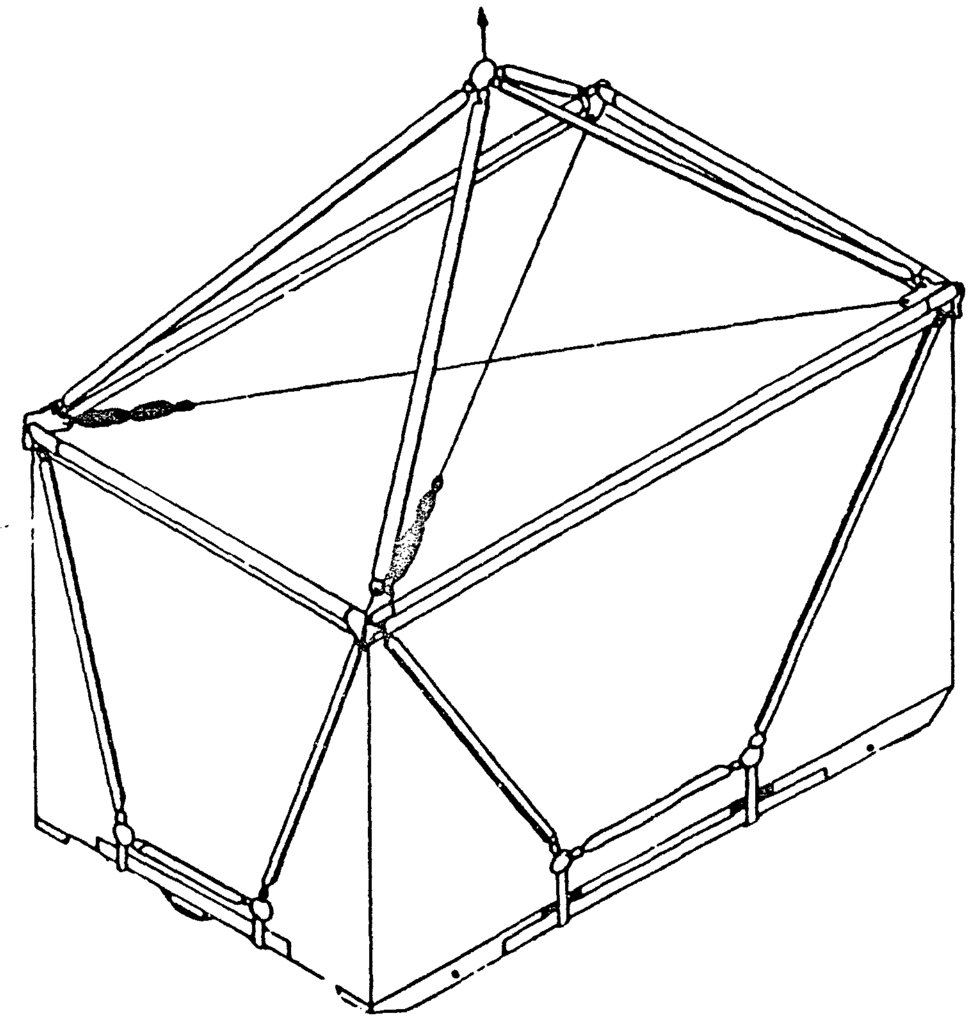

Figure 19. Easy-Fix Design Concept.

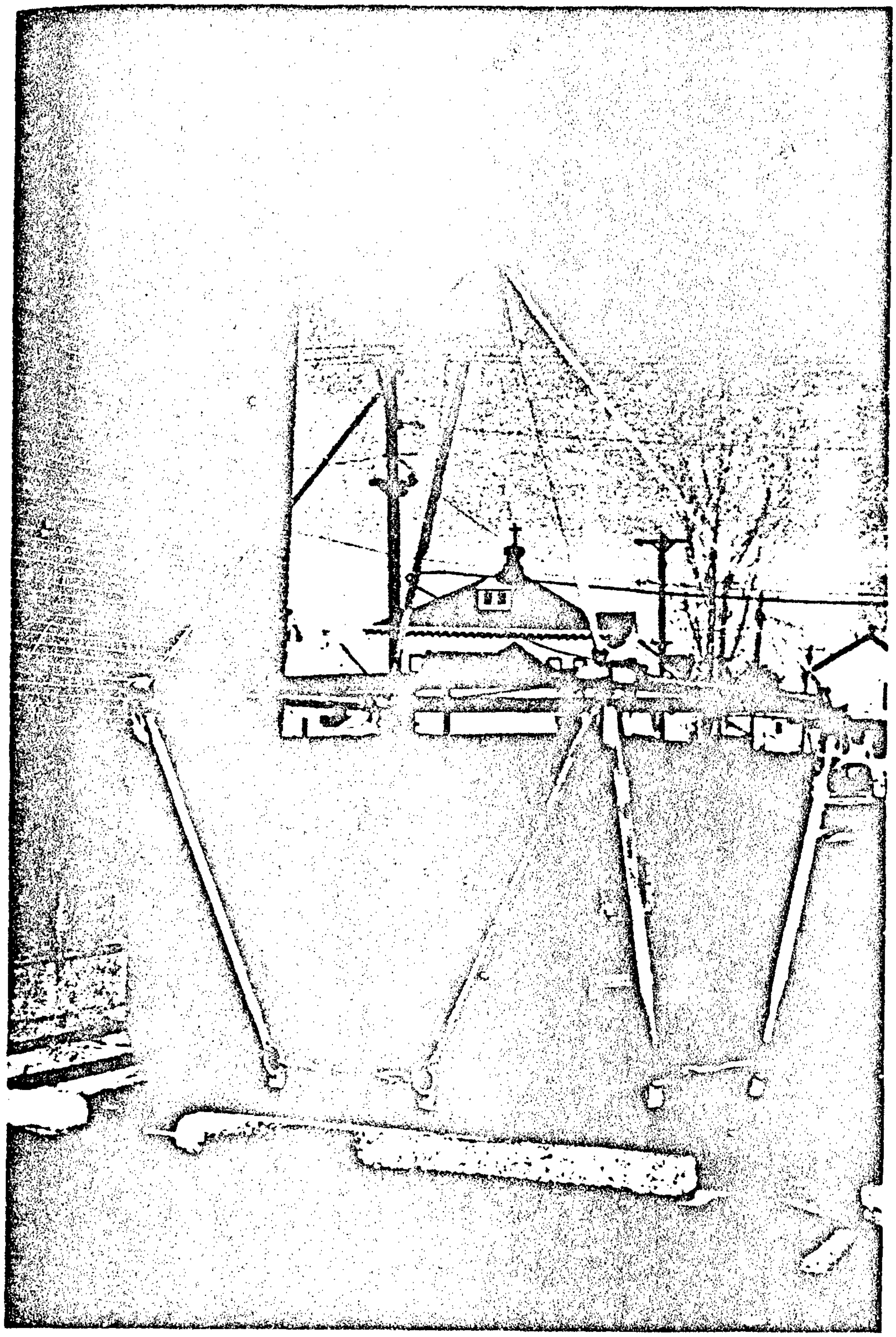

Figure 20. The Assembled Easy-Fix Kit.

system must be much sturdier. An Air Force technical report, AFWAL-TR-87-4114, was published that describes and details the ground rules, design approach, components, and conclusions of this study.

8.2 Repair Kit, "Quick Fix"

UDRI had previously conducted a program to develop the concept of a "Quick Fix" repair kit. This work was performed under Air Force Contract F33615-84-C-5079 and reported in AFWAL-TR-85-4070. The purpose of this kit was to restore both weather and EMI protection to shelters and to maintain and clean EMI gaskets around doors. During this program an unsuccessful attempt was made to implement this kit into the DOD inventory. It appears now that there is no longer interest in a "Quick Fix" repair kit.

9. GENERAL SUPPORT ACTIVITIES

University personnel participated in several activities that were of a general support nature related to tactical shelters.

9.1 ASTM Subcommittee E06.53 Materials and Processes for Durable Rigid Wall Relocatable Structures

University personnel regularly attended and participated in the activities of this subcommittee, whose responsibility is to develop standard practices and specifications for processes and materials used in shelter manufacturing and repair. This participation includes the chairing of task groups charged with the development of new practices and specifications and the drafting and coordination of revisions to new and existing standards.

9.2 Shelter User Survey

A continuing activity in the area of technical support for tactical shelters is the effort to maintain contact with the shelter user community so as to maintain an awareness of problems, needs, and concerns that they have. One tactic pursued to achieve this feedback was the preparation of an unbiased and analyzable survey of the shelter community. One purpose of this survey was to collect information that would serve to focus future R&D activities on issues of significant benefit to the shelter users.

The survey consisted of 35 questions, some multi-part, that addressed every facet of shelter technology, use and experience. The survey was distributed to attendees at the June 1989 Shelter Users Conference at Albany, GA. Thirty-six responses were received with most of these from Air Force users. An extensive analysis of the survey responses was completed and submitted to the Air Force.

10. REPORT ACTIVITY

During the course of this program many of the projects that were undertaken resulted in the publication of individual technical reports. Each of these is referred to in the preceding sections of this report as a source of much more detailed information about that particular project or investigation than is presented in this contract summary final report. Table 57 lists each of these reports.

TABLE 57

TECHNICAL REPORTS ISSUED UNDER CONTRACT F33615-85-C-5094,
TECHNICAL SUPPORT FOR TACTICAL SHELTERS

Report Title	Air Force Report Number	Contractor Report Number (1)	Date of Publication	Authors
Ceramic Armor to Defeat Small Caliber Armor-Piercing Projectiles	WL-TR-91-4094	UDR-TR-89-93	(NOTE 1)	S.J. Bless, R.A. Rondeau, D.R. Askins, S.J. Hanchak, D.L. Jurick
Evaluation of Lightweight Armors for FSP Protection	WRDC-TR-89-4066	UDR-TR-88-142	April 1989	S.J. Bless, R. Rondeau, D.R. Askins
Prototype Development of an Electromagnetic Hardness Assurance Monitoring System (HAMS)	AFWAL-TR-89-4064	AMRC-R-956	May 1988	D.A. Schafer, P.R. Trybus, S.P. Cave
Portable RF Leak Detector Evaluations and UDRI/MRC HAMS Refinements	WL-TR-91-4093	MRC/ABQ-R-1364	(NOTE 1)	D.A. Schafer, G.P. Chapman, A.G. Finci
Design, Development and Demonstration of an Easy-Fix Method for Redeploying Damaged Tactical Shelters	AFWAL-TR-87-4115	UDR-TR-87-56	January 1988	D.R. Bowman
Feasibility Study for the Application of an Easy-Fix Method for Redeploying Damaged ISO Tactical Shelters	AFWAL-TR-87-4114	UDR-TR-87-25	January 1988	D.R. Bowman

TABLE 57 (Continued)

TECHNICAL REPORTS ISSUED UNDER CONTRACT F33615-85-C-5094, TECHNICAL SUPPORT FOR TACTICAL SHELTERS

Report Title	Air Force Report Number	Contractor Report Number (1)	Date of Publication	Authors
A Study of the Floating Roller Peel Test for Adhesives	AFWAL-TR-87-4082	UDR-TR-87-82	Oct. 1987	R.D. Kemp, R.A. Brockman, G.J. Stenger
Long-Term Tropic Environmental Exposure of Army Standard Family (ASF) Rigid Wall Honeycomb Sandwich Panels	WL-TR-91-4141	UDR-TR-91-130	(NOTE 1)	R.J. Kuhbander, D.A. Mikelson, T. Bitzer
Determination of Minimum Adherend Thickness for Climbing Drum and Floating Roller Adhesive Peel Tests	WL-TR-91-4086	UDR-TR-91-35	(NOTE 1)	T.J. Whitney, D.R. Askins

NOTE: (1) In editorial review, not yet published, as of November 1991.

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1. Bless, S.J., "Armor for Air Force Tactical Shelters," AFWAL-TR-82-4163, Vol. I, November 1982.

2. McCormack, Ray G., Christopher Hahin, Richard Lampo, and Paul Sonnenburg, "Study of EMI/RFI Shielding on Tactical Shelters," ESL-TR-80-24, Construction Engineering Research Laboratory, April 1980.

3. Schafer, D.A., P.R. Trybus, and S.P. Cave, "Prototype Development of an Electromagnetic Hardness Assurance Monitoring System (HAMS)," AFWAL-TR-88-4064, May 1988.

4. Anderson, G.P., S.J. Bennett, and K.L. DeVries, Analysis and Testing of Adhesive Bonds, Academic Press, New York, 1977.

5. Gent, A.N., "Adhesion of Viscoelastic Materials to Rigid Substrates II: Tensile Strength of Adhesion Joints," Journal of Polymer Science, Part A-2, Vol. 9, 1971.

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